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Unseen: Advancing Digital Accessibility with Binaural Audio Technology in an Immersive Gaming Prototype

Claudia Susie C. Rodrigues [**Universidade Federal do Rio de Janeiro** | ***susie@cos.ufrj.br***]
Vitoria Nazareth [**Universidade Federal do Rio de Janeiro** | ***vitoriamna@dcc.ufrj.br***]
Ramon O. Azevedo [**Universidade Federal do Rio de Janeiro** | ***ramonoa@dcc.ufrj.br***]
Priscyla Barbosa [**Universidade Federal do Rio de Janeiro** | ***priscyla@cos.ufrj.br***]
Cláudia Werner [**Universidade Federal do Rio de Janeiro** | ***werner@cos.ufrj.br***]

System Engineering and Computer Science - COPPE/UFRJ, Av. Horácio Macedo, 2030, bloco I, sala 044a subsolo - Cidade Universitária, Rio de Janeiro, RJ, 21941-914, Brazil.

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Abstract: The growing significance of accessibility, particularly in the realm of disability rights, is unmistakable. ”Unseen” emerges as a prototype leveraging binaural audio technology to craft an immersive 3D gaming experience, placing a paramount focus on promoting accessibility and digital inclusion. Its primary objective is to deliver a immersive audiogaming encounter, catering to both sighted gamers and individuals with visual impairments. Through a comprehensive evaluation of the prototype, the efficacy of its audiogame interactions and mechanisms was assessed. Valuable insights gleaned from laboratory tests not only pinpointed areas for game enhancement but also shed light on elements that fostered user satisfaction and motivation. These research results notably exemplify promoting digital accessibility in gaming, particularly through the utilization of binaural audio, and the active engagement of individuals with visual impairments in the virtual environment.

Keywords: Virtual Reality, Binaural audio, Accessibility, Visual impairment

1 Introduction

This work is an extension of the paper presented at the II Workshop on User Interaction and Research in Game Development (WIPlay), Maceió, Brazil [Rodrigues *et al*., 2023].

Accessibility, a topic that has been increasingly discussed, has gained significant visibility in recent years. Accessibility is closely related to the rights of people with disabilities [Brazil, 2024]. However, in a broader sense, accessibility is the condition that enables the overcoming of obstacles that represent barriers to the active participation of individuals in various aspects of social life.

In this sense, digital inclusion consists of providing all citizens, in an equal manner, with the opportunity to have access to information and communication technologies (ICTs).

Data from IBGE [IBGE, 2010] shows that in Brazil, there are 35,774,392 people with visual impairments experiencing some difficulty, significant difficulty, or total blindness, representing 14.19% of the population. The degrees of visual impairment encompass a wide spectrum of possibilities, ranging from total blindness to perfect and total vision. From here on, the term ”visual impairment” refers to the range that encompasses from blindness to subnormal vision (low vision).

In this context, the objective of this paper is to promote the culture of digital accessibility and demonstrate that it is possible to recognize and include people with disabilities within their environments. To achieve this, a prototype called ”Unseen” was developed at Lab3D (Virtual Reality Laboratory) in Brazil. This serious game is used in an educational context and primarily targets individuals with visual impairments.

The predominance of visual elements in 3D environments poses a significant challenge for visually impaired individuals, limiting their access to such content. This challenge has garnered increasing attention in research circles, especially with the shift towards graphical interfaces in user design, which has reduced the accessibility once provided by text-based environments. Visually impaired users, who previously navigated text-centric interfaces adeptly through speech synthesis, now encounter heightened difficulties in accessing and comprehending digital content. Consequently, blind users frequently encounter substantial barriers when attempting to engage within virtual worlds, primarily due to the exclusive reliance on graphical interfaces. However, with the use of a technological feature called binaural audio, it is possible to enable their participation, making the experience similar to that of a sighted user. In this sense, a digital game that can be enjoyed by both visually impaired and sighted individuals, using three-dimensional (3D) sound as the main form of feedback, was developed. Both audiences are treated equally, with ample possibilities and opportunities, without sacrificing the fun factor.

The remainder of this paper is structured as follows: Section 2 provides Theoretical Framework. Section 3 describes Related Works. Section 4 presents the Unseen Game and its prototype. Section 5 describes the prototype Evaluation. Finally, Section 6 addresses final considerations.

2 Theoretical Framework

The gaming industry has experienced exponential growth in recent years. However, despite the increasing interest in games, a large group of users is unable to play due to their

disabilities, as accessibility features are often minimal in traditional games available on the market [Cheiran, 2013].

Programs of digital inclusion face numerous challenges in sharing knowledge and information to include these users in the information society. However, [Wrzesinska *et al*., 2021] highlight that young individuals with visual impairments who engage in electronic games tend to exhibit better abstract reasoning skills, improved social interaction and self-confidence, and play more frequently compared to their non-disabled peers.

Visually impaired users rely only on sound. According to [Nesteriuk, 2018], an audiogame is a type of digital game that places sound as its central element. It encompasses mechanics, interfaces, output, and feedback, providing a more accessible digital entertainment experience for individuals with varying levels of vision. In this type of game, sound serves as a substitute for the visual element, and having effective auditory feedback is crucial for an optimal gaming experience. It enables gameplay based on exploration and investigation of the surroundings. Auditory feedback can take various forms, such as the sound of footsteps while exploring the environment, alerts indicating that further progress is not possible, information about whom the interaction is with and the success of that interaction, or confirmation of the player's actions, such as turning right after pressing a related button. These auditory feedback elements ensure maximum immersion, allowing the player to focus entirely on the game in a secure manner. However, persistent audio feedback, even when it provides valuable information, is often annoying for users. An environment that minimizes this discomfort is an environment that will actually be used.

Another crucial feature that can be provided is audio description, which [Bourne, 2007] defines as verbal information inserted between dialogues, aiming to assist blind or visually impaired individuals in understanding what is happening on the screen. It is a technique of describing images, whether static or dynamic, providing relevant information about their audiovisual content. It translates images into words. [Bourne, 2007] clarifies that audio description is not just about describing what is seen but rather what is essential for understanding the work, therefore, it should be connected to it in a way that contributes to the organization of its meaning. It involves a detailed narration of visual aspects such as shapes, sizes, colors, positions, actions, textures, emotions, and more. Audio description plays a crucial role in the life of a blind person, as it provides access to visual information that would otherwise be inaccessible. Imagine watching a movie without being able to see the facial expressions of the characters, the settings of the scenes, or the details of the actions happening on screen. For someone who cannot see, these visual cues are completely lost, severely limiting their understanding and appreciation of the narrative.

Inclusive games are more challenging to develop. According to [Chioccola, 2017], one of the main challenges in designing this type of game is creating games that also appeal to sighted players. An inclusive game should ideally be equally engaging, enjoyable, and challenging for both audiences. Striking a balance between accessibility for visually impaired players and maintaining the interest of sighted players poses a significant challenge in inclusive game design.

Audiogames utilize three-dimensional sounds as a substitute for visual information, serving as an accessible tool for stimulating orientation and mobility through entertainment [Balan *et al*., 2015]. They help identify the direction, distance, and characteristics of the sound source, enhancing the user's sense of reality. By relying solely on the sense of hearing, for example, it is possible to determine the distance from the source of the sound, perceive when someone is approaching, and even discern the direction from which a particular noise or voice is coming. 3D audio guides and enhances the immersion of users, assisting the player in gameplay. For an enhanced experience, it is recommended that the listener utilizes stereo headphones. Consider this scenario: "Imagine immersing yourself in a game set in a bustling hair salon. You can hear every detail around you without needing to physically turn your head: the buzz of clippers as they cut hair, the gentle flow of water from the tap to your right, and the distant ring of a phone in the salon's background."

Three-dimensional sound, or binaural audio, involves the complete manipulation of a person's spatial perception, creating the illusion of a virtual environment and sound source localization, utilizing the human ability to perceive sound in three dimensions. Binaural sound has the capacity to deceive the listeners, making them believe that they are actually present in the reproduced environments. The brain is led to believe that the listener is in a virtual world. Thus, binaural sound represents for audio what virtual reality promises for visuals: the 3D sensation of being in a complex and real environment [Gunzi, 2008]. The binaural audio involves applying a specific frequency to one ear and a slightly different one to the other. Due to its asymmetric nature, the brain combines these two waves, perceiving only the difference between them. For example, by playing a frequency of 300Hz in one ear and 310Hz in the other, the brain will perceive a difference of 10Hz. This frequency difference in the listener's brain results in an immersive experience [Viana, 2020]. The advancement of this auditory experience can be distributed across various platforms and reach a large number of listeners without the audience needing to invest in cutting-edge equipment. Until recently, binaural recording was extremely expensive. Nowadays, to record in binaural format, only a pair of headphones designed to capture 3D audio is required.

The prototype of the Unseen game, developed by the Lab3D team, aims to explore the language of sound and the vast possibilities that the acoustic universe offers in terms of stimulating the imagination. Binaural audio, as a strategy, expands the possibilities of the game's narrative, encompassing aesthetic and technological experiences. The goal is to create a new dynamic that provides an immersive experience for the player.

3 Related Works

In this section, we discuss related works, their connections, and relevant comparisons with the proposed project. The games considered for comparison are The Vale: Shadow of the Crown [Vale, 2024], Audiogame Breu [Breu, 2024], Sound Hunter [Brieger, 2013] and BlindSide [Åsén, 2013].

The Vale is an action-adventure game with over five hours

of gameplay, set in a medieval universe. The main character, a blind castle guardian, must explore a vast environment and face challenges. The game utilizes 3D audio resources and tactile feedback to immerse the player in the game's universe. The gameplay is similar to Unseen, featuring free movement and exploration of the environment through indicative sounds. However, The Vale goes further by allowing the player to also determine the distance of objects through sound, further enhancing immersion. Additionally, The Vale incorporates more gameplay mechanics, such as a sword combat system and an inventory system for navigation, buying, and selling. Scene descriptions are delivered by characters or when the main character asks their traveling companion to describe what they see.

Breu, a game produced by Brazilians and nationally recognized, tells the story of Marco, a young man who lost his vision at the age of 15 and began living with his grandfather in a small countryside town. He hears strange reports of missing residents, including his friends and his grandfather, which leads him to investigate the forest. Audiogame Breu and the Unseen project share some similarities, such as main menus with audio description and an investigative narrative. However, Breu adds a survival horror element, while Unseen has a more visual setting and a different gameplay mechanic. Breu is fully voiced, with each character having their own voice, while Unseen uses synthesized voice throughout the game. Additionally, Breu does not utilize 3D audio technology, which is essential for playing Unseen. Both games allow the player to explore and interact with objects in the environment to uncover clues and progress in the story, but the way this is done is quite different. In Breu, the player cannot move through the environment but instead selects what he/she wants to interact by using the left and right keys and then pressing the ENTER key. In Unseen, the player can move on a 7x7 grid and freely interact with objects in specific cells.

Sound Hunter [Brieger, 2013] is a 3D-based audio-only game developed to explore a new framework proposed in a thesis. Unlike many conventional audio games, the game focuses on utilizing 3D-audio cues for navigation without relying on additional aids or imaginary spatial perception, making it accessible to both sighted and visually impaired players. The game offers players a heightened sense of control and immediate response from the auditory environment. The game addresses the high demand for audio-only games for visually impaired smartphone users, offering simple navigation through hand movements and providing a way to train spatial hearing. Additionally, like the Unseen game, Sound Hunter promotes interaction for both sighted and blind players, aiming to serve as a supportive tool and stimulus for the development of new games intended for this target audience.

BlindSide [Åsén, 2013] is an immersive audio-only adventure game set in a haunting 3D world. Players take on the role of an assistant professor who awakens blind to a city in ruins, plagued by mysterious creatures. Inspired by co-creator Aaron Rasmussen's own temporary blindness from a high school chemistry accident, BlindSide delivers a unique horror experience with sound effects, dialogue, and Gyroscope-enabled virtual reality. The game offers a new level of audio-based horror accessible to both blind and sighted users. Using a gyroscope sensor in the mobile phone system, players can rotate the avatar's facing direction, enhancing immersion and providing a deeper sense of ultra-immersion in audio games. The avatar vocalizes its thoughts aloud, guiding players through the environment and describing objects to assist in navigation and gameplay challenges. By positioning players inside the avatar's mind, BlindSide provides a visceral experience where players can hear and interpret the avatar's thoughts. This mental overview of the surroundings helps players overcome obstacles and fully engage with the game's immersive world. This game offers a sonar, one of the initial ideas considered for implementation in Unseen, although it was later discarded. Furthermore, significant attention was given to the player's three-dimensional immersion, with improvements to the mobile phone's gyroscope sensor. In a mobile version of Unseen, this feature would certainly be added.

The work by [Dudley, 2023] brought a survey through a systematic review with the synthesis of demonstrated strategies to improve the accessibility of Virtual Reality and Augmented Reality applications, as well as the discussion on the pending challenges that must be overcome to improve the accessibility of these technologies. There is a shortage of evidence-based accessibility and design guidelines that directly address accessibility in VR and AR. Because of this, there is a certain lack of awareness related to the exclusionary effects of a disability and the lack of understanding of the accessibility needs and requirements aimed at these technologies. Most of the works use the WCAG 2.1 guidelines [W3C, 2018] for developing web interfaces. Therefore, studies and research that address and investigate these thematic areas are of great importance. Another challenge highlighted by the review [Dudley, 2023] was the difficulty of conducting empirical research, both due to the risks of displacement and the number of participants. The simple fact of inviting users with disabilities to participate in a laboratory study introduces potential ethical concerns related to exposure to risks during the course. As with other research that works with accessibility [Dudley, 2023], there is some difficulty in gathering a representative sample of users with a given disability. The work of [Salamon and Musse, 2014] used musical notes to treat the positions and trajectories of objects. However, the game was not tested with blind participants. An advance and difference in the research and development of Unseen was to carry out the testing of the Genius Game, which also uses progressive musical notes, with both blind and sighted participants who were blindfolded.

Although there are other games that use audio for accessibility, Unseen stands out for the following reasons:

- Equal Experience: While many games only partially adapt their resources, Unseen ensures that blind and sighted players can play on equal terms.
- Educational Approach: Unseen not only entertains but also educates, integrating elements that promote the learning of complex concepts like matrices, which are traditionally difficult to teach to the blind.
- Awareness: In addition to being an accessible game, Unseen also educates sighted players about the experiences of the blind, something that many existing approaches

fail to achieve.

Moreover, the use of binaural audio to create an accessible game for visual impairment players represents a pioneering contribution within the context of this journal. As prior works in this area are limited, Unseen offers a significant and original contribution, advancing the discussion on accessibility in virtual reality gaming.

In the next section, these issues will be explained in more detail.

4 Unseen Game

The Unseen project aims to provide an immersive 3D experience through a digital game. It is designed as a serious game with an educational purpose. The prototype was developed using Unity Engine, along with Visual Studio 2019 software and the Windows 10 Pro operating system, on a desktop computer with the following specification: an Intel(R) Core(TM) i7-7700 CPU @ 3.60GHz processor, 16 GB of RAM, an HD Graphics 630 video card, and STEREO Headphones IG-7537.

The game takes place in the ”Rare Works” Museum Hall, which exhibits three artworks: Abaporu, Mona Lisa and The Mestizo. These three works of art have significant importance in the history of art and global culture. The hall is structured in a grid pattern of 7m x 7m. As the player moves through the hall, he/she can interact with people, who can be either employees or visitors, objects, artworks, and games. For example, “An unknown person has just handed you a Braille note. Press ENTER to read the message: ‘There is a human figure in the artwork Abaporu, a woman in the artwork Mona Lisa, and a man in the artwork The Mestizo’.”

The player wins the game when he/she unravels the mystery and discovers which artwork is the fake one. The target audience includes both visually impaired and sighted individuals. In the game, the player is portrayed as an explorer-type character. He/she is challenged to find clues throughout the salon, attempting to decipher the game’s puzzle. The player explores the entire scenario through interactions to uncover hidden items. While exploring the salon, the player is also challenged to play two mini-games: Genius and Sound Memory Game, with the objective of obtaining more clues to unravel the mystery. In the Genius Game, the player must reproduce the sounds heard in the same ascending sequence presented. In the Sound Memory Game, the player must uncover pairs of identical sounds in a 2x3 table.

The Genius minigame was inspired by an electronic memory and strategy game launched in 1980. Its objective is to memorize sequences of lights and sounds emitted by the device and reproduce them correctly. The original game consisted of a circular board divided into four colors (green, red, yellow, and blue), with a corresponding button for each color. In the center of the board, there was an electronic panel that emitted lights and sounds. The player had to repeat the sequence of colors and sounds activated by the device, pressing the buttons in the correct colors in the same order as they were presented. Each round added a new color, increasing the difficulty of the game.

In the Unseen minigame, the player needs to repeat a sequence of emitted sounds by pressing the corresponding arrow keys on the keyboard: right arrow for when the sound is played to the right, left arrow for when the sound is played to the left, and forward arrow for when the sound is played forward. Each round adds a sound positioned to the left, right, and forward, increasing the difficulty of the game.

The memory game on a 2x3 grid is a variation of the classic memory game, where players seek pairs of identical cards on a board. In the case of the 2x3 grid, the board consists of 6 cards distributed in 2 rows and 3 columns.

The objective of the game is to flip the cards one at a time, memorize their positions, and find the corresponding pairs. Players typically take turns, flipping two cards at a time. If the two flipped cards form a matching pair, the player keeps them face up and earns a point. If they do not match, they are flipped back down, maintaining their original position.

The game continues until all cards have been matched in pairs. The player with the highest number of matching pairs is declared the winner.

In the Unseen game, the variant of the memory game on a 2x3 grid features pairs of cards that emit corresponding sounds when flipped. If a player flips two cards with the same sound, they earn a point.

In addition to providing a fun and challenging experience to exercise memory, this game also addresses the concept of matrices with blind individuals. Developing this cognitive skill may present additional challenges due to the absence of visual references, making this game a valuable tool for this audience.

Unseen stands out significantly from other existing educational and accessible games through an innovative approach that includes the following aspects:

- Equality of Challenges: Unseen captivates both sighted and blind players, challenging them under equal conditions. It ensures that blind individuals have the same opportunities to learn and interact in a three-dimensional environment, promoting true inclusion.
- Translation of Visual to Auditory Resources: The game translates visual resources into auditory ones to allow blind individuals to utilize these elements as well. A clear example of this adaptation is the mini-game ”Genius”, a classic that uses colors and sounds in its sequences, now adapted with three-dimensionally positioned sounds. This fun game attracts and engages players immensely.
- Adaptation of Classic Games: Unseen also adapts the Memory game to use auditory resources, enabling blind individuals to work with matrices. The first version of the game introduces the manipulation of a 2x3 matrix. Through instant auditory feedback, the game reinforces the understanding and memorization of the concept, promoting the development of mathematical skills that can be difficult to acquire otherwise.
- Blind World Resources for Sighted Players: Another innovation of Unseen is the use of typical resources from the blind world for the benefit of sighted players. By raising awareness among sighted players in a purely auditory space, the game allows them to utilize

resources such as audio descriptions and interact with objects important to blind individuals, like a Braille ticket. This goes beyond differentiated navigation with auditory feedback, which is common in other games of this type.
- Binaural Audio Technology: The use of binaural audio technology in a serious gaming context is a significant innovation. It demonstrates how traditional barriers can be overcome with the use of new technologies, providing an immersive and inclusive experience.

In summary, Unseen not only addresses but also surpasses specific challenges that have not been sufficiently tackled by previous works, standing out as a truly innovative approach in the field of accessible virtual reality games.

Other important requirements of the game include: despite being a game without visual resources, it should strive to prevent the player from feeling lost in the salon; the game provides immediate auditory feedback for each player action; through binaural audio, it immerses visually impaired players in the 3D world, offering an immersive experience through positional sound; and it ensures enjoyable entertainment for both sighted players and those with visual impairments.

The electronic game can be described using the MDA model proposed by [Hunicke *et al*., 2004]. This model divides a game into three components: mechanics, dynamics, and aesthetics. Mechanics refer to the rules that govern the game, dynamics are the systems formed by the mechanics, and aesthetics are the emotional responses that the player experiences during the game. Therefore, the use of the MDA model allows us to understand how the game works and how it emotionally impacts the player.

4.1 Mechanics

Within the MDA model, mechanics represent the fundamental elements that make up the game. These elements encompass all the rules, behaviors, and actions that a player can perform within the context of the game.

The rules and mechanics of the game are as follows:

- Using the vertical arrow keys or the ”W” and ”S” keys on the keyboard, the player can take a step forward or a step backward.
- Using the horizontal arrow keys or the ”A” and ”D” keys on the keyboard, the player can rotate 90 degrees to the right or left, directing his/her character within the grid.
- When approaching an object with interaction possibilities, a musical note indicating the position of the object will play. For example, a sound to the right will be emitted if the object is positioned to the right of the character.
- When hitting a wall, a distinctive sound will play, indicating that the player cannot move in that direction.
- Pressing the ENTER key allows the player to interact with objects or people, or for audio prompts.

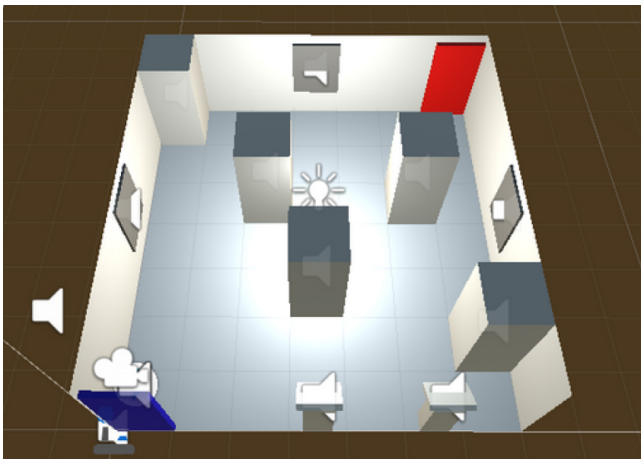

Figure 1. 3D environment representing the Museum Room with all objects available for interaction.

4.2 Dynamics

In the MDA model, dynamics are the result of the player’s actions through the mechanics.

Although the game does not have a visual interface, it is represented by a 7x7 grid. Clues, people, artworks, and mini-games (Sound Memory Game and Genius Game) are located within the cells of this grid. As the player moves through the salon, they hear a signal indicating the presence of an object for interaction, either in front, to the right, or to the left. The player positions himself/herself in front of the object, presses the ENTER key, and receives a clue, an audio description of an artwork, or the opportunity to interact with a mini-game.

The feedback that the player receives for smooth navigation includes:

- A musical note indicating the position of an object for interaction.
- A distinctive sound indicating collision with a wall.
- Footstep sounds when moving through the salon.
- Audio providing hints to solve the game’s puzzle.
- Audio descriptions of the three exhibited artworks in the museum.
- Audio descriptions of menu options within the game.

Due to the importance of the audio played during the game, which needs to be heard by the participants at different volumes and sometimes only in one of the earphones, it was decided not to provide the same audio to the evaluators. This decision would make it challenging for them to track the player’s progress and location during the game. Therefore, during the evaluation (which will be detailed in the next section), it was chosen to provide the evaluators with a visual representation of the environment to facilitate their understanding. **Figure 1** illustrates the 3D environment in the Museum Room, showcasing all the objects available for interaction. It is worth noting that none of the test participants had visual access to this environment during the study.

4.3 Aesthetics

In the MDA model, aesthetics refers to the emotional responses evoked in the player through his/her interaction with

the game. In the Unseen game, the following aesthetics were identified: Challenge, Sensation, and Discovery.

”Challenge” is defined as the feeling of overcoming a task skillfully and efficiently. It encompasses the sense of accomplishment and satisfaction that arises from successfully navigating the gameplay challenges.

”Sensation” is associated with pleasurable sensory stimuli, including auditory feedback, that emerges from the player’s actions. It aims to engage the player’s senses and create an immersive and enjoyable experience.

Finally, ”Discovery” is the sensation of exploring uncharted territory. It encompasses the excitement and curiosity that arise when uncovering new information, interacting with objects, and discovering hidden aspects of the game world.

These aesthetics work together to create a compelling and engaging experience for the player, providing a sense of accomplishment, sensory pleasure, and a desire to explore further.

5 Evaluation

After developing parts of the game prototype, it was necessary to carry out an evaluation of the game to identify interaction problems that could harm its usability. The evaluation involved collecting qualitative and quantitative data through questionnaires, observing users interacting with the audiogame and conducting a semi-structured interview. The research aimed to discover interaction elements that left the user satisfied, motivated, prone to errors and to verify whether the methods of navigating the environment were clear.

The test was carried out in person at COPPE’s Lab3D (Virtual Reality Laboratory), located at the Federal University of Rio de Janeiro (UFRJ), using headphones and a computer with the prototype installed. With the participant’s permission, the session was recorded to collect additional information that could be expressed by the participants verbally during the test and interview. Six user tests were carried out, the first being considered a pilot test. The tests involved three sighted users and two blind users. Participants performed the tests under the same interaction conditions, only via audio (**Figure 2**) and should have mastered the use of computers and electronic games. To structure the test tasks and activities, three areas of the audiogame were considered: Sound Memory Game, Genius Game, and Museum Room.

Despite the game focus being sound, the researchers relied on the graphical interfaces developed in the prototype to monitor user interaction during the test. In the Museum room, it was possible to monitor and observe interaction and movements through space in real time through the software’s graphical interface (**Figure 1**). The Sound Memory Game and Genius Game had an interface that demonstrated errors and successes during the interaction. Players wore headphones and it was not possible to have two audio outputs. Therefore, the researchers were unable to simultaneously listen to the audio that users were listening to. In the case of the Sound Memory Game, the researchers followed the visual information displayed on the screen about the number of pairs

Figure 2. Participant navigating the Museum Room wearing headphones and blindfolded.

formed by the player. The main challenge of this mini game was the time limit of 2 minutes to complete all 3 pairs of sound cards, which could generate a defeat screen only if this time was exceeded. In the case of the Genius Game, the researchers kept track of how many sequences of musical notes the player had successfully achieved. The game ended when the player reached the 8th sequence or when he/she missed a note, displaying the defeat screen in the latter case.

Because the laboratory is located on a difficult-to-access campus, students from the university’s Bachelor’s degree in Computer Science were invited to facilitate transportation to the test site. Furthermore, care was taken to guide the blind participants who were accompanied by the team to the designated test location as there were stairs to go down to the basement where the laboratory is located. Upon arrival at the testing site, an introduction was provided describing the design and objectives of the assessment. Next, a printed Informed Consent Form was provided to sighted participants, while it was read aloud to blind participants. In addition to the Consent Form, previous clarifications were adopted for users to point out the risks, albeit minimal, that they could be subject to by participating in the test. Highlighting the need to interrupt and return to complete the tasks, or even withdraw from participating in the study, if they felt a little tired, uncomfortable, embarrassed or stressed. To guarantee the privacy of data disclosure and access to the information produced, the collected data will be stored and maintained in the laboratory database linked only to the main project coordinator. After data collection/analysis, all information will be permanently removed from the virtual database and stored on a physical device, under the responsibility of the research coordinator. To ensure traceability and maintain identity secrecy and confidentiality, participants were identified numerically. The dissemination of results and publications at conferences and scientific events will not make any mention of their identification, using numerical identification to cite individual responses, which will not be traceable and, therefore, guaranteeing privacy in the dissemination of data. Subsequently, each participant answered a pre-test questionnaire with data about their profile and experience (**Table 1**).

At this point, sighted participants were asked to blindfold their eyes to begin performing the tasks. To ensure the game is playable by any player, regardless of prior experience or guidance, each of the three test modules contains recorded audio instructions. Participants were asked to listen to all the instructions for the activities in each module. In addition, instructions for the test tasks were given to the partic-

Table 1. Comparative table of qualitative data of participants' profile.

	P1	P2	P3	P4	P5
Age	20	19	20	24	43
Schooling	Higher education	Higher education	Higher education	Higher education	Higher education
Gender	M	M	F	M	M
Visually Impaired Person	No	No	No	Yes	Yes
Gaming Habit	Yes	Yes	Yes	Yes	No
Gaming Platforms	PC, Smartphone	PC, Smartphone	PC, Smartphone, Console	PC, Console	PC
Frequency of playing games	Sporadically	Sporadically	Sporadically	Two or more times a week	Never(discouragement)
Player skill level	Intermediary	Experient	Beginner	Experient	None
Previously played audiogames	No	No	No	Yes	Yes

ipants, which will be detailed in the next item. All interactions were recorded on video and also noted in the printed follow-up script. Only after all tasks were completed did the researchers ask the post-test interview questions. Some structured interview questions were related to the following categories: Game Instructions (Are the instructions clear? Did anything seem difficult to interpret/understand?); Types of Sounds (Are the sound effects intuitive?); 3D Audio Position (Is the sound "position" easy to distinguish? Can you clearly/easily hear where the sound is coming from?); Location (Was it easy to find the works to listen to the audio description?); Content (What did you think of the descriptions of the works?); Usability (Did you have any difficulties when testing the game? What do you think should be improved in this game to make it more accessible and easier to use?).

5.1 Assessment Tasks

In the Museum Room, the task proposed looking for game tips, which were the clues spread throughout the room, and finding a work of art to listen to the audio description. After listening to the game instructions and freely exploring the environment, participants had time to complete the task. The objective of this task was to evaluate whether users could navigate and orient themselves within a 3D sound environment, in addition to checking whether they would have difficulty interacting with the elements spread around the room. Once participants completed the tasks, the game ended, and the researchers moved on to the next testing module: the Sound Memory Game.

In the Sound Memory Game, in addition to listening to the instructions, participants performed a sound test that demonstrated the game's interaction sounds. In this test, participants could hear in advance the sounds of success, error, card turning, anticipating the sounds that would be heard during the game. After this, participants were asked to explore the 6 cards and find card number 6. Once a participant indicated that he/she had found it, the game was restarted and the participant played the full game. The purpose of testing this module was to assess whether users were able to understand the game instructions and perceive different types of sounds during the game.

At Genius Game, it was also possible to perform a game sound test after listening to the instructions. The game was then reset so that the participant could play and reach level 5, which represents a higher level of difficulty. If they wished, they could try to complete the game by reaching level 8. The objective of testing this module was to identify whether users could perceive the different locations of the 3D sound.

5.2 Assessment observations and interview reports

The Museum Room proved to be the most challenging task, where participants took the longest period of time to complete the tasks. Some participants reported feeling lost, unsure of their location, or having difficulty finding their way around. One of the main challenges in developing the prototype was to reduce the possibility of players getting lost in the room's corridors. Therefore, in the initial instruction, information about the dimensions of the hall (7 x 7) was used. It was observed that this information was considered by some participants who were interacting slowly, one of them reported that he was counting the number of clicks relating to the number of steps around the room. Some participants' comments during the interview were: "Actually, locating myself in the Museum Room and knowing which direction I was going, at the beginning, was the hardest part" (P1); "At first, I was lost, walking diagonally" (P2). Another information given in the instructions for this game module was the use of the ENTER key to interact with people, objects, and mini-games. At this point, the prototype provides sound feedback (collision sounds, footsteps, and audio descriptions) for each of these interactions, being a resource used by players to assist in their location in space as well as to find interactive objects. In the interview, participants made suggestions to improve the sound when interacting with objects and a different sound when encountering walls. One of the blind participants reported the absence of other noises he perceived in closed environments, such as background conversations, to enhance the immersive experience.

In the Sound Memory Game, the sound test feature that showed the different types of sound for each interaction in

Table 2. Comparative table of quantitative test data showing the average time, in minutes, taken by each participant to complete the task.

Task time (minutes)	P1	P2	P3	P4	P5
Sound Memory Game	3	1	2	3	1
Genius Game	1	1	1	1	2
Museum Room	8	5	3	10	4

the game was considered one of the facilitators for understanding the mechanisms of this game module. Regarding this game, participant P4 emphasized during the interview: "The instructions are correct, and the audio test is so clear that it doesn't even need documentation. The sound effects were easy to remember and understand to match." It was clear from the test that the game instructions were accurate and understandable. In addition to being the module considered by test users to be the easiest to play and the sound of the cards turning is intuitive.

In the Genius Game, participants found it easy to identify the location of the simulated sound in a 3D environment. A positive aspect was the use of different types of sounds to facilitate recognition. Participant P1 stated, "I could definitely tell the position of the sound." A better clarification was identified regarding the game's mechanism: despite the module's instructions informing that it would be sounds increasing sequentially, one of the participants was unsure and asked to redo the task. P4 pointed out: "I found it easy, but it wasn't clear that it was a progressive sequence. I thought this would happen automatically." With this, another description could be created in the instruction or another way to emphasize the sequencing in the module to assist in understanding and completing the task.

5.3 Qualitative and quantitative analysis

As a result of the game evaluation (**Table 2**), the average time to complete the tasks in the Museum Room was 5.33 minutes for sighted participants (P1, P2 and P3) and 7 minutes for blind participants (P4 and P5). The average time to complete tasks in the Genius Game was 1 minute for sighted participants and 1.5 minutes for blind participants. Finally, the average time to complete tasks in the Sound Memory Game was 2 minutes for both sighted and blind participants. Therefore, the individual average time for each task remained very close for both sighted and blind participants. Even though blind participant P5 was the only participant who declared that he did not have the habit of playing (**Table 1**), he did not demonstrate difficulty in completing the test tasks. It was also observed that despite participants declaring different levels of gaming skill (**Table 1**), the average task execution time was consistent. As a result, the different user profiles were able to perform all the tasks established in the test without giving up.

Through the time indicator and reports in the interviews, all participants found the Museum Room more difficult, as expected by the researchers, due to its greater complexity and need for free exploration. Despite the test task providing a moment of free exploration before carrying out the task, participants reported that they had difficulty finding their way around, finding the objects and works of art spread around the room as it was their first contact with the game. In the interview, they declared their interest in playing again and continuing to explore the environment to learn and discover other sounds in the environment. Just like in the Genius Game, some participants, despite making mistakes on the first attempt, continued exploring to achieve the highest sequence stipulated in the task. Some reported the need to concentrate in this game to identify the direction of the sound and the need to adjust the volume of the sounds.

Another characteristic observed in the participants' profile was their previous experience with audio games. The 3 sighted participants had never tried an audio game, and the 2 blind participants already knew this type of game (**Table 1**). One of the participants stated that he had already tried the audio games available on the DOSVOX system (https://intervox.nce.ufrj.br/dosvox/ferramentas.htm). Even with the difference in previous experience, everyone managed to complete all tasks without help and without giving up, no differences were observed in understanding the mechanisms and performance of the tasks.

In the interview, feedback from the blind participant regarding the feeling of the game experience was: "It's simple, but it's a fun game, an incredible pastime. I never thought I would see a structure like this, especially because it was created by visionary researchers who care about developing for this audience and making it accessible. It is a commendable initiative." This demonstrates the need to encourage more and more research and projects in the area of technology to establish digital accessibility in their games.

According to [Chioccola, 2017], the Unseen game prototype proved that it was possible to develop an inclusive game, as it is equally appealing, fun, and challenging for both audiences. As a conclusion to the evaluation, it was observed that both sighted and blind participants felt immersed in the built environment. Using binaural audio technology, it was possible to involve a blind participant in the 3D world, an essentially visual environment, and therefore very limited for this type of audience. A blind participant responded in the interview: "I felt immersed in the 3D world, it's cool, and the navigation is interesting."

5.4 Post-test iterations

Through the test, it was possible to identify occurrences that would cause problems or some difficulty in interacting with the game. In general, the game's weaknesses are related to the lack of customization, clearer sound feedback and the recognition of spatial location in the 3D environment driven by sounds. This way it is possible to identify the needs for improvements and refinements in the prototype. Below are future changes and suggestions that can be considered in the development of accessible 3D audio games:

- Avoid using numeric keys to access extensive menu options. Some participants mentioned that it was difficult to determine the position of the number on the keyboard and remember the options available to navigate the menu labeled with numbers. Web browsing with screen readers follows an ordered sequence. Therefore, it was recommended to use the keyboard arrow keys for

all menu navigation.

- To promote an experience that leaves no doubts and avoids errors, there must be an audible indication of the end of longer audio tracks. As sound is the only interaction resource in the audiogame, there are no other senses to be explored. Sound must provide clues both for moving around in space and for indicating existing objects. In addition to the sounds of interaction with the game: beginning or end of the interaction, success or failure of the interaction. This was one of the strengths of the Sound Memory Game as it made it possible to test these features. Therefore, it is necessary to reinforce auditory feedback and/or use some sound resource to indicate the beginning or end of an audio track. There were at times doubts among participants regarding the end of the initial instruction and audio description of the works.
- Anticipating the sound resources that would be found in each game was an element that facilitated understanding. Participants found it easier to play the Genius Game and the Memory Game because they were prepresented with the interaction sounds as an audio test at the beginning. As next steps to be taken, an audio test for the Museum Room game should be implemented to help players understand the different forms of interaction in the more complex environment.
- Explore other resources to improve location awareness in the Museum Room. The biggest challenge was in fact the spatial orientation within the Museum Room. This was one of the main problems identified during the assessment as it involves several types of sounds: footsteps, walls, objects - just as researchers had already identified the difficulty in other sound games such as the [Breu, 2024]. It is necessary to continue studies and test other ways of implementing additional resources to further facilitate spatial localization within an audio-only 3D environment. In the study by [Åsén, 2013], it is possible to observe the survey of navigation resources that could be developed and tested with users to verify their effectiveness in recognizing spatial location. One of the suggestions was the use of a radar system.

6 Conclusions

With the development of the Unseen game prototype, it was possible to realize that the use of binaural audio for games that include visually impaired individuals still has a long way to go. Even with examples of some related works, the gameplay needs to be improved. However, the prototype serves as an example that aims to immerse this target audience in a 3D world, which until recently was only available to sighted individuals. In this project, sound is employed similarly for both sighted and blind users, overcoming a significant barrier and enabling people with visual impairments to access 3D applications. Based on the evaluation conducted, it is clear the need for a similar path to follow for this type of game to best meet the needs of this new market niche.

One of the main limitations of the prototype identified is the lack of a screen reader, which would allow visually impaired individuals to control the speed, voice type, and other settings with ease. The initial idea of the game was to have sounds positioned in different locations to create an immersive experience for the player, but this kind of feature needs to be carefully calibrated. In this first version, however, this feature was not implemented. The audio would have filled the environment, illustrating what was happening in that space in a manner similar to audio description. It would provide a detailed description of all important visual elements, contextualizing them to facilitate scene comprehension. In addition to providing entertainment, this harmonious sound environment would promote greater autonomy and inclusion for blind individuals.

Despite advancements in 3D technology, visually impaired individuals still face significant barriers when it comes to accessing 3D world games. Therefore, the main contribution of this research is that it has proven the need for an inclusive game, allowing individuals to experience, understand, and suggest new initiatives and opportunities to be explored. It has the potential to pave the way for further advancements in inclusive gaming and promote accessibility in the gaming industry.

6.1 Future Work

As future work, this project aims to be expanded by incorporating screen readers that allow personalized configuration of the audio to be played. This feature will enable visually impaired players to tailor their gaming experience according to their individual needs, thus enhancing usability and accessibility.

Additionally, the project seeks to enhance positional ambient sounds to enrich the player's understanding of what is happening in the explored salon. By improving the accuracy and richness of audio cues, Unseen aims to create a more immersive and intuitive environment, which is crucial for the engagement of visually impaired players.

The development team also plans to add different levels of gameplay and introduce new mini-games that challenge the player. These enhancements will offer a variety of experiences and maintain the interest of both visually impaired and sighted players, promoting longer and more meaningful engagement.

Unseen has the potential to significantly impact the field of accessible virtual reality gaming. By setting a precedent for the use of binaural audio and comprehensive auditory feedback, it encourages other developers to consider similar approaches in their designs. This can lead to a more inclusive gaming industry where accessibility is a standard consideration rather than an afterthought.

Future research could explore the integration of more advanced haptic feedback systems, providing another layer of interaction for visually impaired players. Additionally, studying the long-term effects of immersive audio environments on learning and skill acquisition in both visually impaired and sighted users could yield valuable insights.

Another promising direction is the development of community features that allow players to share custom audio settings and strategies, fostering a supportive and collaborative gaming community. This would not only enhance the user

experience but also provide researchers with valuable data on user preferences and behaviors.

For users, particularly those with visual impairments, Unseen offers a unique opportunity to engage with VR content in a way that is both enjoyable and educational. It demonstrates that high-quality, accessible gaming experiences are achievable and can significantly enhance the quality of life for individuals with disabilities.

For designers and developers, Unseen serves as a model for creating inclusive content. It highlights the importance of considering accessibility from the outset and provides practical examples of how to implement effective auditory feedback and inclusive design principles. This can inspire more developers to prioritize accessibility in their projects, ultimately leading to a more diverse and inclusive gaming landscape.

In summary, Unseen not only aims to provide an engaging and accessible gaming experience but also sets the stage for future innovations in the field of virtual reality accessibility. By continuing to expand and refine its features, Unseen can contribute to the ongoing effort to make gaming more inclusive for all players.

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Authors' Contributions

Claudia Susie C. Rodrigues contributed to the conception of this study. Priscyla Barbosa, Vitoria Nazareth and Claudia Susie C. Rodrigues performed the experiments. Claudia Susie C. Rodrigues is the main contributor and writer of this manuscript. All authors read and approved the final manuscript.

These are the authors' contributions using the CRediT Taxonomy:

Conceptualization: All authors

Methodology: Claudia Susie C. Rodrigues

Software: Vitoria Nazareth, Ramon O. Azevedo, and Claudia Susie C. Rodrigues

Validation: Priscyla Barbosa, Vitoria Nazareth, and Claudia Susie C. Rodrigues

Formal Analysis: Priscyla Barbosa

Investigation: All authors

Data Curation: Priscyla Barbosa and Vitoria Nazareth

Writing Original Draft Preparation: Claudia Susie C. Rodrigues, Priscyla Barbosa, and Cláudia Werner

Writing Review and Editing: All authors Supervision: Cláudia Werner and Claudia Susie C. Rodrigues

Project Administration: Cláudia Werner

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Competing interests

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Availability of data and materials

The datasets generated and/or analyzed during the current study are available in http://lab3d.coppe.ufrj.br/unseenData/

References

Balan, O., Moldoveanu, A., and Moldoveanu, F. (2015). Navigational audio games: an effective approach toward improving spatial contextual learning for blind people. *International Journal on Disability and Human Development*, 14(2):109–118. DOI: https://doi.org/10.1515/ijdhd-2014-0018.

Bourne, J. (2007). *The impact of ITC Guidelines on the style of four English audio description scripts.(in Spanish)*. Hurtado, Catalina Jiménez (ed). Traducción y accesibilidad. Frankfurt: Peter Lang.

Brazil (2024). Decree no 5296 of december 2: 2004 - general standards and basic criteria for promoting accessibility for individuals with disabilities or reduced mobility. (in portuguese). `https://www.planalto.gov.br/ccivil_03/_Ato2004-2006/2004/Decreto/D5296.htm`, accessed: 18 October 2024.

Breu (2024). Audio Game Breu. `http://www.audiogamebreu.com.br`, accessed: 18 October 2024.

Brieger, S. (2013). Sound hunter: developing a navigational hrtf-based audio game for people with visual impairments. *Proceedings of the Sound and Music Computing Conference 2013, SMC 2013, Stockholm, Sweden*, pages 245–252.

Cheiran, J. (2013). *Inclusive Games: accessibility guidelines for digital games (in Portuguese) [Master's Thesis, Institute of Informatics]*. Federal University of Rio Grande do Sul.

Chioccola, V. (2017). Audio games: Accessibility and inclusion in game design (in portuguese). *Conic - National Congress of Scientific Initiation*, 5.

Dudley, J., Y. L. G. V. e. a. (2023). Inclusive immersion: a review of efforts to improve accessibility in virtual reality, augmented reality and the metaverse. *Virtual Reality*, 27:2989–3020. DOI: https://doi.org/10.1007/s10055-023-00850-8.

Gunzi, A. (2008). *Three-dimensional sound: generation methods and reproduction modes (in Portuguese). Master's thesis, COPPE Electrical Engineering Program*. Federal University of Rio de Janeiro.

Hunicke, R., LeBlanc, M., and Zubek, R. (2004). Mda: A formal approach to game design and game research. *AAAI Workshop on Challenges in Game AI*, 4(1).

IBGE (2010). Census. `https://www.ibge.gov.br/estatisticas/sociais/populacao/`

9662-censo-demografico-2010.html?edicao=9749&t=destaques, accessed: 18 October 2024.

Nesteriuk, S. (2018). Audiogames: Accessibility and inclusion in digital entertainment. *Lecture Notes in Computer Science*, 10917:338–352.

Rodrigues, C., Nazareth, V., Azevedo, R., Barbosa, P., and Werner, C. (2023). Unseen: a 3d immersive experience game for visually impaired individuals. *II Workshop on User Interaction and Research in Game Development (WIPlay), Maceió, Brazil*, pages 13–27. DOI: https://doi.org/10.5753/wiplay.2023.236096.

Salamon, N., J. J. and Musse, S. (2014). Seeing the movement through sound: Giving trajectory information to visually impaired people. *2014 Brazilian Symposium on Computer Games and Digital Entertainment (SBGAMES)*, pages 165–172.

Vale (2024). The Vale: Shadow of the Crown. https://store.steampowered.com/app/989790/The_Vale_Shadow_of_the_Crown/, Accessed: 18 October 2024.

Viana, L. (2020). Immersive audio in podcasts: the binaural resource in the construction of fictional narratives (in portuguese). *Studies in Journalism and Media*, 17(2):1984–6924.

W3C (2018). Web content accessibility guidelines (wcag) 2.1. https://www.w3.org/TR/WCAG21/, Accessed: 27 August 2024.

Wrzesinska, M., Tabala, K., and Stecz, P. (2021). Gaming behaviors among polish students with visual impairment. *Int. J. Environ. Res. Public Health*, 18. DOI: https://doi.org/10.3390/ijerph18041545.

Åsén, R. (2013). Game audio in audio games: Towards a theory on the roles and functions of sound in audio games. http://du.diva-portal.org/smash/searchref.jsf;jsessionid=b0ea5773168d0e99565b3772a288?pid=diva2:682971&searchId=null, accessed: 18 October 2024.