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VR Balls: Using Acoustic Tools to Increase VR Accessibility for Blind People

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Mestrado em Informática

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2024

Acknowledgments

I would like to thank firstly my adviser João Guerreiro, who supported and guided me through the process of this dissertation, challenging me to bring out my best work and pushing me to create the final product I can now present as my Master's thesis. I would also like to thank my Co-advisors Tiago Guerreiro and André Rodrigues, for all the discussions, insights and support in fleshing out this project.

I would also like to thank Fundação Raquel and Martin Sain, and all the participants who shared their time, for their collaboration and willingness to participate in this project.

I would also like to thank my family for all the support, not only in the last year but the years leading up to here. To my parents, siblings and nephews, thank you for believing in me and for making the hard times seem less hard.

Finally, I want to thank my friends, particularly those closest, for all the good moments and memories created in the journey leading to here. Your company gave me strength more often than not. I also want to give a special thanks to Marta, for always trying her best to keep me going and for her unwavering support in all my endeavors.

To everyone who supported me along the way

Resumo

A interação com ambientes virtuais tem sofrido várias alterações e inovações recentes, que permitem não só que os utilizadores possam interagir com ambientes mais complexos de maneiras mais criativas e completas, mas também que os possam navegar e explorar de uma forma que seja mais semelhante à de um espaço real. A Realidade Virtual (RV) trouxe a possibilidade de interagir com um espaço de uma forma imersiva e interativa, simulando a presença de um utilizador num ambiente tridimensional.

Esta interação é, no entanto, particularmente focada numa componente visual, o que torna a participação nestes ambientes inacessível para individuos com deficiências visuais. Embora algumas aplicações já explorem alternativas, de forma a que a informação do ambiente possa ser dada através de meios não visuais, continuam a não existir alternativas generalizadas de forma a que a interação com estes ambientes não se limite apenas a utilizadores sem problemas visuais. Para além disso, estas alternativas são baseadas em dar a informação ao utilizador sem permitir que esta seja descoberta de forma natural, por exemplo dando informação explícita sobre alguma secção do ambiente sem permitir que o utilizador a consiga obter através dos seus próprios meios. Isto elimina a componente de exploração e descoberta, que, para além de ser comum em experiências deste tipo, aumenta o envolvimento do indivíduo com o ambiente.

Desta forma, surge a dúvida: como tornar estes ambientes mais acessíveis sem tirar ao utilizador a liberdade e a componente de descoberta do ambiente e dos seus elementos, sem que a soluçao seja um produto único e não transversível a outros ambientes. Dado que existe um impedimento com a transmissão da informação pelo meio visual, a via sonora é a melhor solução para a passagem de informação espacial, uma vez que permite simular, através de várias alterações ao som, vários tipos de informações, como distâncias, dimensões espaciais e referências. Assim, foi estudada a utilização de ferramentas acústicas como meio de recolha e transmissão de informação, permitindo a interação com ambientes de RV de forma acessível e completa, implementando-as de forma a que possam ser utilizadas em diferentes contextos.

Estas ferramentas foram desenvolvidas com a forma de bolas, uma vez que estas são uma forma familiar e com usos relativamente intuitivos. A forma de uma bola e a sua capacidade de ressaltar e ricochetear em diferentes objetos permite, através do som produzido pelo contacto com os mesmos, o qual, em conjunto com a sua intensidade, permite distinguir proximidades com objetos e, através de outras características do som, o material destes mesmo objetos.

Para além das suas propriedades físicas, queremos explorar as capacidades destas bolas enquanto fontes de som, permitindo a sua utilização enquanto referências. Uma bola que produza

um som específico, quando colocada numa determinada localização, permite ao utilizador criar um ponto de referência através dessa bola em relação ao ambiente que o rodeia, permitindo que o ambiente seja mapeado de forma mais interativa e intuitiva.

Assim, as VRBalls limitam-se aos atos de atirar e de pousar bolas como referências, uma vez que estes atos podem conter bastante complexidade e implicar vários casos de uso. Bolas com a finalidade de serem atiradas contra superfícies contêm diferentes configurações em termos de material, mais pesado ou mais leve, que lhes permite saltar mais ou menos, e obter, desta froma, informação mais ou menos localizada. Bolas com o intuito de serem usadas como referências sonoras têm opções de diferentes sons e até de inputs de voz do próprio utilizador, para uma referência de som totalmente personalizada.

De forma a que estas ferramentas possam ser testadas, construímos ambientes acessíveis com a disposição espacial de uma casa, uma disposição de espaço familiar a qualquer utilizador. Estes ambientes dizem-se acessíveis por implementarem várias componentes que auxiliam à interação com o mesmo. Para além da existência de feedback háptico e sonoro em cada ação começada pelo utilizador, como por exemplo a criação de uma instância de uma ferramenta, o movimento é acompanhado pelo som dos seus passos e o áudio é espacializado, ou seja, simula as condições físicas de um som no mundo real.

Para além destes ambientes destinados exclusivamente ao estudo, foi também desenvolvido um *asset* derivado do desenvolvimento do protótipo utilizado no estudo com utilizadores. Este foi testado em diferentes projetos para determinar a sua adaptabilidade a diferente ambientes de produção, permitindo a adaptação dos *scripts* e componentes desenvolvidos de forma a que a sua integração noutros projetos fosse facilitada e de forma a que pudesse ser lançado como um *asset* oficial na Unity Asset Store, permitindo a sua utilização por parte de terceiros, de forma a aumentar a acessibilidade nos seu próprios projetos.

Implementando estas características e as ferramentas através do Unity3D, com recurso aos óculos Meta Quest 2 e ao motor de som FMOD, foram planeados e efetuadas sessões de teste com 14 utilizadores cegos, com duração média de 75 minutos, de forma a perceber a a utilidade e validade deste conceito, procurando perceber como é que as VRBalls influenciariam a exploração e orientação num ambiente virtual, e quais seriam as mecânicas mais úteis das mesmas. Foram realizadas tarefas de exploração, em que os utilizadores tiveram a liberdade de explorar o ambiente da forma desejada, e tarefas de navegação, em que os utilizadores foram convidados a realizar a distância mais curta entre dois pontos distintos do ambiente. Estas tarefas foram feitas tanto com recurso às ferramentas como sem recurso às mesmas, dando aos utilizadores liberdade total na sua utilização. Foram também conduzidas entrevistas aos utilizadores, de forma a compreender as opiniões dos participantes sobre a utilidade e funcionalidade das ferramentas e de que forma a sua utilização potenciou a sua experiência no ambiente virtual.

De entre os vários participantes puderam ser observados diferentes desempenhos, no entanto, os resultados foram na sua maioria inconclusivos, nomeadamente em termos de sucesso na utilização das VRBalls, sendo que o feedback dos utilizadores foi no geral positivo, reconhecendo

utilidade e potencial nas ferramentas. No geral, estes foram quantizados e associados a resultados numéricos de forma a que a análise pudesse ser o mais objetiva possível, excluindo a entrevista, na qual o feedback foi analisado e onde foi feito um levantamento das questões mais pertinentes levantadas pelos utilizadores e quais as opiniões gerais do grupo de estudo, analisando-as de forma qualitativa.

Dos vários resultados, tornou-se claro que a utilização das VRBalls como ferramentas de apoio à exploração à orientação foi preferida para a exploração por grande parte dos utilizadores. Dado que estes tiveram a liberdade de usar as suas mecânicas livremente, podendo escolher quais as mais úteis para a sua exploração, houve uma distinção clara na preferência por determinadas mecânicas, nomeadamente a da utilização preferencial de VRBalls de referenciação relativamente ao uso de VRBalls com o propósito de serem atiradas. Não foram identificadas distinções de maior relevo entre as explorações feitas nas diferentes modalidades, no entanto acreditamos que se deveu principalmente à dificuldade das tarefas pedidas e não necessariamente a falhas das ferramentas, o que implica que a continuação do trabalho neste projeto poderá trazer resultados diferentes e que tragam uma nova perspetiva relativamente aos resultados obtidos nesta dissertação.

Em conclusão, através do trabalho desenvolvido e do estudo realizado com utilizadores invisuais, podemos acreditar que, com a continuação deste trabalho, a utilização destas ferramentas pode ser uma mais valia para que se criem mais condições de acessibilidade na vivência dos espaços virtuais por parte de pessoas cegas, permitindo uma melhor experiência em diferentes contextos e garantindo que utilizadores cegos não são excluídos da utilização de tecnologias modernas por falta de mecânicas de acessibilidade nas mesmas.

Palavras-chave: Realidade Virtual Inclusiva, Cegos, Áudio Espacializado, Ferramentas Acústicas, Acessibilidade

Abstract

Virtual Reality (VR) is a technology that had many advancements and improvements over recent times. By allowing users to partake in immersive and interactive experiences, exclusive and unique moments can be provided. Unfortunately, VR's core content is mainly transmitted through sight, which creates an accessibility barrier for blind people. Even when there are workarounds for these issues, they either are not too developed or not usable outside of a research environment or give all the information to the user, eliminating potential opportunities for exploration and discovery that are so fundamental to a VR experience.

As such, we wanted to explore the use of acoustic tools in a VR setting, creating them in such a way that users can get spatial information about the environment and reference it as they go along. Through this process, we also want users to keep the ability to explore and navigate the environment without being told what to do or how to obtain the information in an environment. Finally, we want users to be able to use these tools in different contexts without extensive adaptation for each scenario.

Given that they have both the shape and the behavior physical balls would have, the tools have a familiar shape and can have familiar uses, such as throwing and bouncing. By giving users the ability to throw different-sized and weighted VRBalls, and also using them as continuous audio references, information about the space can be easily conveyed through sound. We tested these tools with blind users, in order to understand their potential and how users would fare with them, through exploration and navigation tasks in different virtual environments, collecting results from the tasks and asking for feedback on their usability. This allowed us to evaluate their use and consider how they could be an advancement in accessibility.

Keywords: Inclusive Virtual Reality, Blind, Spatial Audio, Acoustic Tools, Accessibility

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Acronyms

HMD Head Mounted Display

HRTF Head Related Transfer Function

O&M Orientation and Mobility

SEQ Single Ease Question

UX User Experience

XR Mixed Reality

VR Virtual Reality

Chapter 1

Introduction

1.1 Motivation

Virtual Reality (VR) is a technology that has become increasingly relevant in recent years. Yielding many use cases in different fields, this relevance has been accompanied by the birth of more complex and innovative projects, making VR a stand-out innovation in the technology world. Many products and improvements have been released in recent years, making VR not only a more complete and realistic experience but also contributing to making it more known and available to the general public.

This spread, however, also highlights a general accessibility problem. Given that the feedback one receives in this type of experience is mainly visual, blind people are mostly left out of the group of people that can fully partake in this experience, since a big part of it is inaccessible to them, and the information given this way is not generally transmitted through other senses. The issue is that even though this is a known problem and some existing tools try to make VR accessible for blind people [15], these are generally not accessible in a widespread way, being used mostly in research and self-contained environments, making it so that the potential these tools could have is not spread to other contexts.

VR uses mostly 3D audio, and there is an extensive study on how 3D audio can be used as efficiently as possible, whether to understand how orientation is affected [8, 10] or how users perceive it relative to static or moving objects [20, 21]. These audio configurations generally are not adaptable to other environments, so it is important that they are flexible and manageable depending on the environment.

Even if some accessibility tools are used, these mostly tend to give information to the user in such a way that they are guided to specific paths or locations. This is helpful in the sense that it facilitates the fulfillment of the experience's goals, but takes away the exploration component that could otherwise create an entirely different experience and is key in some contexts. Essentially, users are given full information and context about several components of the environment, for example, layouts of space and locations of certain objects. This not only eliminates the exploration component of the VR experience but also deprives users of being allowed to discover the environment for themselves.

As such, we can conclude that there is an interesting object of study in terms of tools that can not only bridge the accessibility gap that is naturally created in VR, but also not take away the experience from the user, maintaining an exploration and discovery component in the virtual space and also giving most of the information the user could not access otherwise.

1.2 Objectives

Our main goal with this project is to study the use of acoustic tools as a viable solution for accessibility in VR environments, allowing users to not only use them as a way of bringing accessibility to the virtual space, but to also use them freely, opening the possibility of not only explore an environment without constraints, but also keep a sense of discovery during the exploration. We want users to not feel limited while using these tools, giving them the agency to use their features as best they can without any type of limitations, giving them the ability to explore their use as they prefer. We want to understand how these tools can influence and impact the user's experience in exploring and navigating virtual environments, mainly which capabilities, such as orientation or cognitive mapping, are improved in a series of tasks.

To achieve this, we performed a study with 13 blind participants, allowing us to study these tools' performance and how users fared with them in accessible virtual spaces, through exploration and navigation tasks, giving us insights not only into how blind users understand these tools and how they evaluated their usefulness but also how their functionalities influenced the experience as a whole.

We also have the goal of releasing these tools publicly as an asset on the Unity Asset Store, so other people can use these tools in their projects and create more accessible VR environments, adapting them easily to different settings.

1.3 Contributions

Our main contributions with this thesis are:

- The conceptualization of a set of acoustic tools, and the implementation of its uses in an accessible virtual environment, both with auditory cues and haptic feedback available during the entire course of their use inside a virtual environment;

- The analysis of a study with 13 participants, with a set of exploration and navigation tasks in virtual environments, along with an interview about their opinions on both the tools and the experience, including a deeper analysis of the reasoning behind the choice of features used and the strategies chosen during the course of the tasks;

- An accessible asset available on the Internet, containing the final iteration of the developed tools, implemented to be usable in multiple environments outside of the ones built for the study.

1.4 Structure of Document

This document is organized as follows:

- **Chapter 2 – Related Work:** An analysis of the state of the art is provided, studying how blind people interact with virtual environments and the role of audio in these interactions, not only as a way of conveying information but also how the players choose to use it.
- **Chapter 3 – VR Balls:** An explanation of the concept behind VRBalls, our design and implementation of these tools, and the creation of the Unity Asset derived from it.
- **Chapter 4 – User Study:** A presentation of the conducted study and its structure, explaining the study's setting, process and methodology.
- **Chapter 5 – Results:** A review of the results obtained during the study, both qualitative and quantitative, the comparisons between the different participants' choices and an analysis of the obtained values.
- **Chapter 6 – Discussion:** A discussion of the obtained results, how they answered our research questions, what results we could draw from them and which were the lessons and limitations learned from the process.
- **Chapter 7 – Conclusion:** Final thoughts on the conducted work, the results and takeaways from it, and future work to be done.

Chapter 2

Related Work

In this section, we will discuss three main topics relevant to this work. We will analyze 1) accessible VR for blind people, 2) accessibility in virtual environments in a gaming context and 3) how sound can be used as an accessibility tool.

2.1 Virtual Reality for Blind People

Following Gigante et al.'s definition [16], Virtual Reality is "the illusion of participation in a synthetic environment rather than external observation of such an environment. VR relies on three-dimensional (3D), stereoscopic, head-tracked displays, hand/body tracking and binaural sound. VR is an immersive, multi-sensory experience". VR allows users to explore environments in a first-person perspective while being fully immersed in them. Since blind users cannot use visual cues and references to transverse these environments, having the necessary aid to compensate for the lack of information obtained is needed to provide an adapted experience to the one a sighted person would have.

Orientation is greatly influenced by one's capability of cognitive mapping. Cognitive mapping involves learning a route and reviewing it from memory, including all aspects of coding, processing and retrieving information from the environment [14]. This is an essential component in the virtual experience of visually impaired individuals since the spatial information cannot be given visually as it would be the case of a sighted person.

Research on this topic has been made, in which information was collected on how spatial cognition can be improved in acoustic VR, to improve cognitive mapping [4]. There are also studies such as the ones by Afonso et al., where the ability of cognitive mapping of both sighted and blind people is compared, depending on the type of sensory feedback in the virtual environment (haptic or auditory) [3], similarly to another study of the same author, in which the object of study is the amount of sensory feedback necessary for better mapping, also with both types of individuals [2]. The general conclusions are that locomotion and the use of spatial audio improve the results of spatial cognition, while also comparing the different results shown in tests with both blind and blindfolded participants, mentioning how the amount of time a user has been blind affects these results.

Numerous experiments have been made in regards to the exploration of virtual spaces, in the themes of strategies used to explore the areas [26], comparing the cognitive mapping resulting from virtual and physical exploration of spaces and the reconstruction of these virtual spaces [11, 27, 33, 38, 42]. These are generally based on having blind people explore these environments freely, or through specific tasks and commands, in a virtual environment. Afterward, their performances are tested in regards to strategies used to create cognitive maps, which sounds make the most difference and can be used to help the roaming of the environment (the sound of a finger snap for example, as seen in Picinali et al's work [38]), as well as how the configuration of certain sounds emitted may influence the cognitive mapping of the environment.

Allowing users to explore virtual environments that are copies of virtual environments has also been shown to be a better option for orientation and creating mental maps of a given space instead of solely relying on the exploration of its physical counterpart, since users have more freedom to collide with objects and move faster without any physical effort, thus making it easier and allowing for a more complete cognitive mapping of the space [27].

These methodologies have proven to be effective both in testing blind people's capabilities of orientation and capacity in learning inside the virtual environment, but also in the subject of how the knowledge obtained from the virtual experience translates to the real world and its corresponding physical spaces. For example, studies such as the one by Guerreiro et al. [22], are based on the learning of physical routes through the use of a smartphone and walking through them later on. The exploration of these spaces is generally made through the use of controllers, joysticks, or keyboards, but advancements have been made in regards to immersion and, as such, treadmills can also be an option for the exploration of virtual spaces [25]. Besides the aforementioned example, accessible locomotion can also be simulated with the use of virtual canes, just like in the real world, through smartphones that recreate the feedback a white cane would give on an auditory form [47], or canes with adapted feedback to virtual responses, where a cane is adapted to provide the feedback the virtual world would give if it was physical [43].

Some work is also related to the social aspect of VR. Social platforms such as VRChat [1] and Facebook's Metaverse allow users to connect and interact with each other in virtual settings, but accessibility is once again a weak point. Creations like the VRBubble [24], in which users get auditory feedback from the presence of other avatars around them, try to cross that bridge by making VR interactions easier. A study by Collins et al. [9] utilizes guides in a virtual environment and allows users to get feedback from the various guides in different contexts, even allowing the users to get to different places with "Shared Movement", linking themselves to the guides in order to be taken to the desired destination. Besides the social factor of interacting with the guides, this was shown to have potential as an improvement for virtual guidance systems. Gonçalves et al. [19] studied how blind people prefer to navigate and interact inside these populated virtual environments.

In the subject of objects and events inside the virtual environment, research was made in the sense of understanding how to utilize auditory feedback to substitute feedback that would be given visually. In Guerreiro et al.'s [21] work, a design space was created with a series of categories to be explored (such as sound type and audio field) in a boxing context inside a VR environment. In this work, it was concluded that these virtual environments can provide accessible experiences since there is more control on the user's side and that the use of a design space can be beneficial to create better experiences, given that there is no set of configurations that are preferred by most of the participants.

Being a spectrum, visual impairments are not limited to a full-on lack of sight. As such, for less severe visual impairments, Zhao et al. [48] created SeeingVR, a set of tools that can be injected into Unity-based games or be used as assets, whose main objective is to increase the accessibility of a specific environment by changing or highlighting elements, in a way that is adaptable from user to user, depending on the type of its condition.

2.2 Exploring Virtual Environments Through Gaming

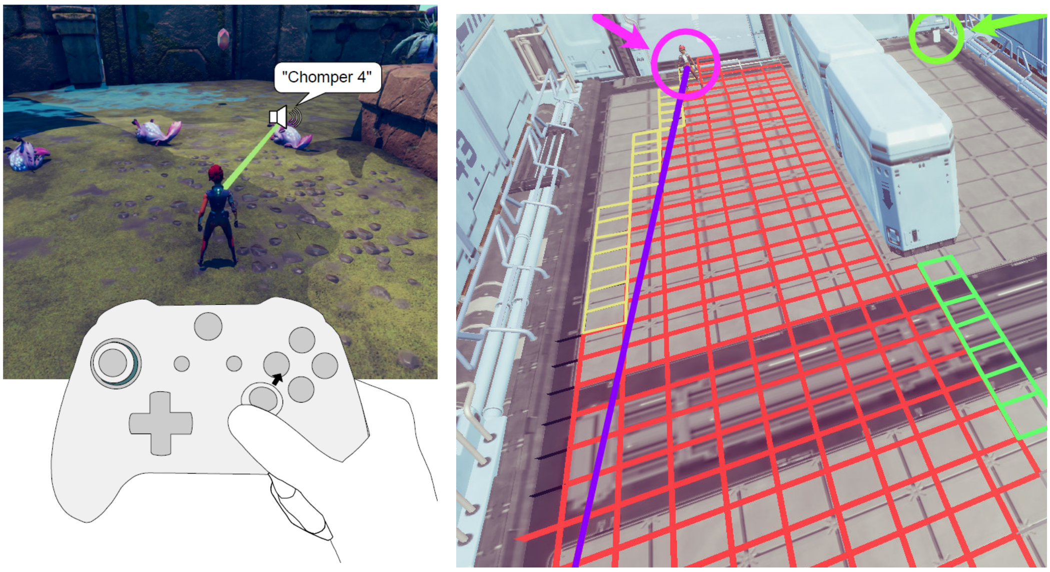
Gaming is the mainstream way of accessing virtual environments, which makes it an important gateway for the exploration of the spaces. Given this fact, it is also necessary to understand which strategies and ways of playing increase accessibility in blind gaming. Also, since the user study we performed involves the exploration of virtual environments, it is important to understand how this exploration can be made in less conventional ways.

As large as the gaming industry is, it still has a lot of problems with accessibility. Games like The Last of Us Part II [13] bring a lot of accessibility features to reduce the impact of blindness on regular playing, but it is not enough to bring the full experience to the table. As such, audio games are very prevalent in the blind gaming community, since their main output is sound instead of graphics [46].

Audio games are followed by a large community of, mostly, visually impaired gamers, designers, and developers [46]. Although this community is relatively large, it is a general opinion that these games lack the same quality as mainstream games, lacking variety and interest. This could be for several reasons: a study done in 2012 refers that, in 10 years, only 400 audio games were created, compared to the thousands of games made in that period [15]. Also, the lack of blind game designers and developers makes gaming harder, since they do not know what it is like to play a game without vision and do not always understand the amount of complexity that games can have [46], which, coupled with lack of budget, affects the possibility of better and more complex blind gaming. Variations of these games are also used in research experiments, as seen in the previous section.

To play regular games, visually impaired individuals must rely on different strategies and tools to work around the limitations the games set them. Without the use of screen readers, generally external to the game, it would be impossible for gamers to play, or have a close experience to the one intended originally for sighted people. Other tools include automation mods, auto aiming mechanism and tools to facilitate playing like NavStick, in which the idea is the same as a white cane, but the object to which the player is aiming reproduces a sound that identifies it [35].

The issue with some of these tools is the fact that they eliminate the discovery component of the games: for example, automation mods and auto-aim bots take away the opportunity to discover new elements of the world because it is assumed that the player cannot find them in any other way. Tools like Surveyor [37] try to maintain these elements that are lost to accessibility tools, giving the player the ability to still roam and interact with the environment freely and without spoiling the experience.



(a) (b)

Figure 2.1: Accessibility Tools - (a) Navstick [35], (b) Surveyor [37]

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We can see many practical solutions to gaming with visual impairments on Youtube, as there are many YouTubers who play AAA games and have visual impairments. According to a compendium of many strategies blind players use [18], although they face many barriers, blind gamers find effective strategies to be able to play these games and get the most out of them. Another tool is to play these games with the assistance of a third party, whether that is someone who is by the player's side or through feedback given through live chats with people assisting a live broadcast of a game's playthrough, as is the case with blind streamers.

Inside the gaming environment, players use various strategies to get around the lack of visual knowledge of movements and environments. Some of these include the placement of landmarks - points of interest that make the orientation task easier. One example of this use could be marking every doorway with a torch, so the player knows he is going through a door or a passage, thanks to the specific sound the torch produces. This mechanic can essentially be summarized as placing specific objects with specific sounds in key locations. Other ways of testing the environment are random explorations of space, moving around and understanding where walls are and where floors change and/or stop existing (through collisions and the sound of steps). This can also be done by interacting with the surrounding objects by "attacking" them [18], with the example of the usage of the sword in Legend of Zelda.

It should be noted that, while playing these games, after a few rounds of exploring, blind people tend to have an easier time orientating themselves through the game's maps and recreating them without external help, in comparison to blindfolded people [39]. This implies that not only their cognitive mapping skills without vision are greater than those of sighted people, but also that their spatial awareness through senses other than vision is also very refined. The player can use strategies as mentioned before, or use built-in tools, such as audio menus or directional scanners. Nair et al. [36] studied the preferences of spatial awareness tools, depending on the intended function (such as understanding scale and shape, orientation and placement of items), and which functions are the most useful, concluding that the most important is the orientation and position, and scale and shape of a room are the least important, also concluding that the most useful tools, in a general way, are directional scanners.

Some researchers have also developed an accessibility metric to classify VR games, based on many factors such as directness, expansiveness, the energy required to play them, and more, using a formula to calculate a final rating of accessibility using famous games such as BeatSaber to test this method [44]. There are also games directed at blind individuals that try to emulate the regular experience. One example is VI-Bowling [34], which is essentially an accessible version of the bowling modality in Wii Sports. This way, the player can use a remote controller similar to the Wii to play bowling, similarly to the way it is played on the Wii Sports.

2.3 Utilizing Audio as an Accessibility Tool in VR

For people with visual impairments, types of sensory feedback other than sight are essential for the performance of everyday tasks. These would include feedback related to all other senses: touch, smell, hearing and taste. We will be mainly focusing on audio and haptic feedback to a small extent since those are the most prevalent in VR and virtual environments. Audio is the main focus not only because it is the most utilized mode of feedback, but also because it is one of the main ways of assuring blind orientation in any environment.

It should be noted that there exists no study that confirms the lack of ability of visually impaired people to execute tasks with the same capacities as sighted people [17], given that the experiences are adapted. It has also been shown that people with visual impairments have a greater capacity for acoustic localization [20], and the usage of audio cues improves orientation [7].

As such, some measures must be taken so that lack of sight does not become a barrier to the interaction with virtual environments. One of the main ways of ensuring the full accessibility of these experiences is the smart usage of audio. The navigation of virtual environments can be vastly improved if some conditions are met. According to Façanha et al's [14] literature review of orientation and mobility (O&M) in virtual spaces, 4 requirements should be met in order to allow a user to make the most of his orientation capabilities in the virtual environment. These are the usage of 3D spatial audio, making a sound louder as the person is closer to its source, the association of specific sounds to specific objects, as in associating a different sound to every object so the user cannot misinterpret it; making sure every movement is heard, for example collisions and steps, and the usage of helping audio to describe the environment and the task at hand. Research also shows that the preferences of sound settings and how sound should be presented vary from user to user [14, 21, 29], although the main characteristics presented earlier seem to be consistent in user's preferences.

In addition to hearing the various movements and sounds associated with specific objects, auditory feedback can also be given through echoes. Using echolocation, users can emit sound waves and understand layouts of spaces through the way sound rebounds in objects. Research shows that, although training would be required so that the user could improve, this is a viable way of exploring and orientating oneself through the virtual spaces [5, 6], assuming that there is constant use of this method since it is a skill that can be easily lost [12].

Audio feedback can also be aided by external devices such as BlindAid [28] (or its variations [43]), which gives haptic feedback as well as audio feedback while a user explores a virtual environment, working as a joystick. The EyeCane [31] is also a device created to be an ETA (Electronic Travel Aid). It works by emitting an infrared beam and calculating the distance to a determined object by calculating the amount of time it takes to receive the signal back and emitting a frequency according to the distance. It can also be used in virtual environments as evidenced in [30].

It is also important that the correct HRTFs (Head Related Transfer Functions) are calculated. These are essentially the relationship between the origin of the sound and the positions of both ears (one function for each), calculating how an individual's ears perceive the sound, varying from person to person due to different physical characteristics. These usually come integrated into the sound system associated with the virtual environment, but there are other ways to generate it, for example with artificial neural networks, as shown in Haraszy et al.'s work [23].

Given that the user can freely navigate these environments, the question now becomes how the audio presented within the experience can be utilized to the best of the user's abilities. Experiences in 3D Audio environments show that, with training and users accustomed to these technologies, results improve in testing [8], which means more possibilities for appliances with virtual surround sound.

2.4 Main Takeaways

Throughout the last sections, work related to the most relevant subjects to the development of this dissertation was presented. There are some conclusions we can take from each section that are useful in the rationale and development of our concept.

Although there is extensive research on how virtual environments can be best explored and result in better cognitive mapping, there is no use of an adaptable tool for multiple contexts. Most of the mentioned environments tested are local and/or recreated manually from real spaces, and most tools are also used and designed to be used in specific spaces. This shows that presenting an accessible alternative that can be used in multiple different contexts is a viable path for the project. There is also no use of acoustic tools in VR exploration that we are aware of, which again presents a knowledge gap that can be explored.

We have also explored how blind gamers navigate through virtual environments in games. Although many strategies are utilized, and some of them, such as the use of landmarks in games like Animal Crossing [18], will inspire some of the mechanics of the acoustic tools' development, most strategies are based on the use of in-game features as accessibility tools, even though that is not their original purpose. As such, the lack of exploration of in-game tools with accessibility functions that are transversal to different contexts motivates the implementation of this project. Beyond this, even if we accept that these tools will not be built into the games, most of them will actively cut the learning and exploration process of the game, due to automation, giving the player some information he would otherwise have to find for himself, or leading him to determined locations, which leaves the feeling of an inferior game experience. By creating tools that allow the player to get an accessible experience without harming the exploration component of a game we believe that a viable solution can be presented.

Finally, relative to audio feedback, we explored how many audio tools are used. This project intends to explore how the sound of impacts and landmarks throughout the virtual space can influence the orientation and exploration, with configurations that can be as generalized as possible, in order for them to able to be used in different contexts where the tools can be implemented.

Chapter 3

VRBalls

In this section, we will explain our approach following the analysis of the current state of the art and how we implemented this project. Firstly, we will explore the concept and the solutions we found, and afterward the design we proposed and its respective implementation.

3.1 Concept

As seen, accessibility in virtual environments is a subject that is widely studied. Naturally, some solutions have been presented, such as the ones discussed in the previous section, but not every solution can be used in different contexts and publicized in such a way, making it so that a lack of accessibility continues to exist. What we propose is that if tools can be versatile and used in different contexts, maybe they can also be used in a more diverse set of applications and not be limited to some test environments. By association, making these tools functional in different contexts also gives users the freedom to use them however they so desire and make them adaptable to different circumstances, by not only giving a set of options that can aid in the experience, but also be a means to discover information more dynamically, making the entire experience more fluid.

By allowing the user to use these tools freely, he can decide for himself which of the implemented features are more useful in each section of the virtual space, while also allowing for a more interactive exploration given that all the tools are in the user's domain and there are no exterior incentives to indicate where to use the tools. Giving the user all this freedom allows us to understand how each feature is useful in an exploration and navigation context, and how different users use these mechanics to bridge the accessibility gap.

VRBalls are, as the name indicates, ball-shaped tools. This choice is due to the fact that balls have the shape of a sphere, a simple volume that can be used in a versatile way, and most of all, intuitively. Balls are familiar objects with mostly familiar uses. For example, if a ball is picked up, depending on its weight, it can be thrown against an object and/or in someone's direction so it can be caught. Different balls can also be associated with different uses, for example, a bowling ball will be thrown differently than a ping-pong ball. Assuming this ball can produce a sound, it can be used to identify a specific location or place or object solely through its respective noise.

3.2 Design

We discussed the number of actions the users could perform with the tools, understanding just how large the set of features could be, and decided to limit their mechanics to throwing and placing, given that these can carry a lot of complexity and variables within themselves. Features like having a landmark VRBall going back and forth through a specific path or giving it the ability to be controlled remotely, allowing the user to explore a specific path before actually walking through it, were discarded mainly because their complexity could overload the user.

As such, the main mechanics of VRBalls are throwing and using them as landmarks, producing a pre-defined sound for the entire time it is present on the map. Once a user creates a ball, that ball can have either throwing or landmarking settings. Depending on which hand the user creates the ball, it can have one of these two purposes.

3.2.1 Throwing Balls

When a VRBall is created with the throw feature, it can be thrown by the user in any direction, with as much strength as the user wants to put into the throw. This freedom allows the user to decide which information he wants to obtain, whether it be the length of a hallway, the dimensions of a room or the distance to a certain object. This throw is similar to one of a real ball, which adds a degree of realism that is only possible through VR. These balls cannot be picked up after being released, not only to allow a more dynamic and efficient exploration, but also to make sure that once a ball is colliding with objects, the information flow is not interrupted by the user picking up the ball. On the other hand, this information flow should not be too long, as such, these balls disappear after a while as a way of not taking up all the space in the environment and to make sure no unwanted and unexpected feedback is present.

This specific VRBall is accompanied by another variable: weight. A user can choose a pre-defined weight for the ball, lighter than the standard ball to obtain more information in a single throw or heavier than the standard ball to obtain a more particular piece of information.

Using a lighter ball, a user can, for example, throw it randomly in any direction and, due to its reduced size and bounciness, it will hit more surfaces, bouncing more, and, therefore, increasing the amount of information the user can obtain with a single throw. A heavier ball, on the other hand, is not able to go as far and bounce as much, given that it is larger and harder to throw in greater distances, so it is a way to identify if there's a specific object nearby and to confirm small distances, since it will mainly roll until it stops.

The audio feedback the ball produces varies according to the distance the user has from it, given that the audio is spatialized. Harder throws will also result in louder sounds, and bounces from bigger heights will also result in louder sounds, due to gravity.

3.2.2 Placing Balls

A VRBall that is created with the intent of being placed is spawned ideally in the opposite hand where the ball to be thrown was created, making it so that the user can associate a different ball to each hand, allowing for less confusion in their creation. Originally, these balls were intended to be affected by gravity, making it so that the user would have to throw them to the desired place, and only allowing them to work when associated with a surface. This approach was so that the VRBalls could be physically ”realistic”, however, this would mean that large rooms would have large spaces without possible landmarks producing sound at ear level. So, the choice was made for the VRBall's position the be the one where the user releases it.

The VRBall will produce a continuous spatialized sound, which means the user will hear it differently depending on where he is. By using this feature, a user can reference a specific point in the map, allowing him to recognize it and, by association, the location he meant to landmark. The creation of a VRBall can be undone, as a way of avoiding placing mistakes, allowing for the elimination of the last created ball and so forth.

The user can also choose the sound he wants the ball to produce. This way he can use different sounds to landmark different places, making the mental mapping process easier, since there is more than one sound to associate with the objects. Beyond some pre-defined sounds, a user can also record his voice and save it to a VRBall, allowing for totally personalized audio feedback.

Finally, as for the continuity of the feedback, options such as making it different according to the proximity of different users, or making it feedback-dependent, meaning the user would choose when to have it, were considered but discarded. By making the sound continuous and spatialized, more distance means the user can hear it less if he is further away, and with wall occlusion included in this, volume can be even lower. By also making the sound continuous, the landmarking process is more direct and allows the user to map the environment with ease, while also limiting the tools to strictly referencing and exploring.

But the user can also want to limit the amount of information the landmark VRBalls are producing and may want to more easily identify their position, which can be confusing at times if a number of audio sources are producing sound. As such, the user can turn the audio sources on and off through a shockwave feature, changing their playback state from the closest one to the furthest. This way, a user can filter the information he wants to receive more cleanly, while also allowing the VRBalls to maintain their position.

3.3 Prototype

The implementation of this project suffered an iterative process until the final prototype was reached. Throughout this process, Unity3D was used to build and configure the VR environments and mechanics, which were then tested and discussed up until the final result was obtained. To access the virtual spaces and interact with them, we used the Meta Quest 2 headset and its controllers. Relative to sound, we used the FMOD sound engine [1], a widely used software that allows for more control and realistic audio configurations inside virtual environments.

3.3.1 Mechanics

In order to move through the environments, the user can use the joystick on the left controller, pushing it in the intended direction to walk. We chose to allow the user to move like this since it is one of the most common and most explored ways of locomotion in VR environments [40, 32]. In order to turn and/or change direction, the user only needs to move his head (and his body in association if desired), looking at the intended direction. Originally this could also be done with the right controller's joystick, but was discarded since the body's movement could fully perform this mechanic and it was redundant to keep it, along with the fact that it could influence motion sickness.

VRBalls can be created in both hands. Each hand creates a specific type of VRBall, allowing for an easier separation of controls. We chose to make the right hand the one where balls intended to be thrown were created since it is the dominant hand for most people, making the throwing action easier. In order to create a VRBall the user must press the grip button on the respective controller (see Figure 3.3). This ball will be spawned in the user's hand and will not disassociate from it until the grip button is released.

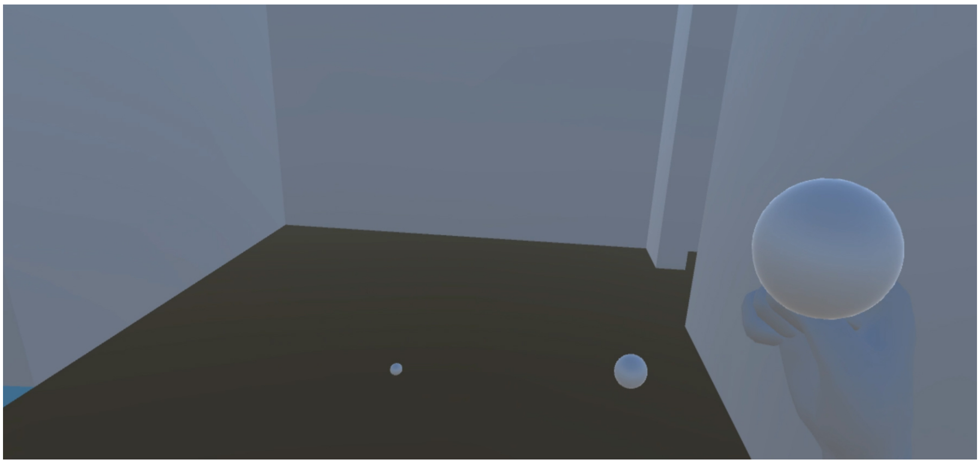


Figure 3.1: Throwing VRBalls - A regular and heavier VRBall on the floor while the user prepares to throw a light VRBall

Right Hand

As mentioned, the VRBalls created in the right hand are configured to be thrown against surfaces. To throw it, the user must release the grip button at the right time, so that the ball follows the intended trajectory, just like throwing a ball in the real world. The ball follows the trajectory

[1] Available at `https://www.fmod.com/unity`

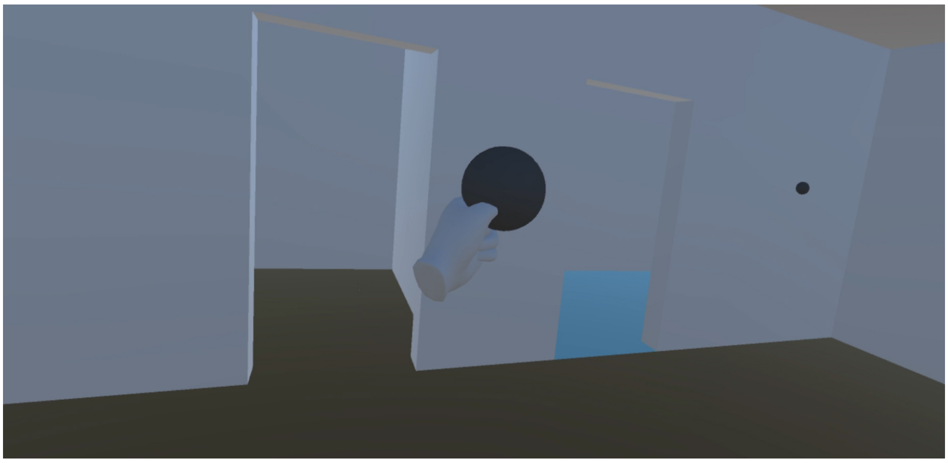


Figure 3.2: Placing VRBalls - Placing a Landmark near another

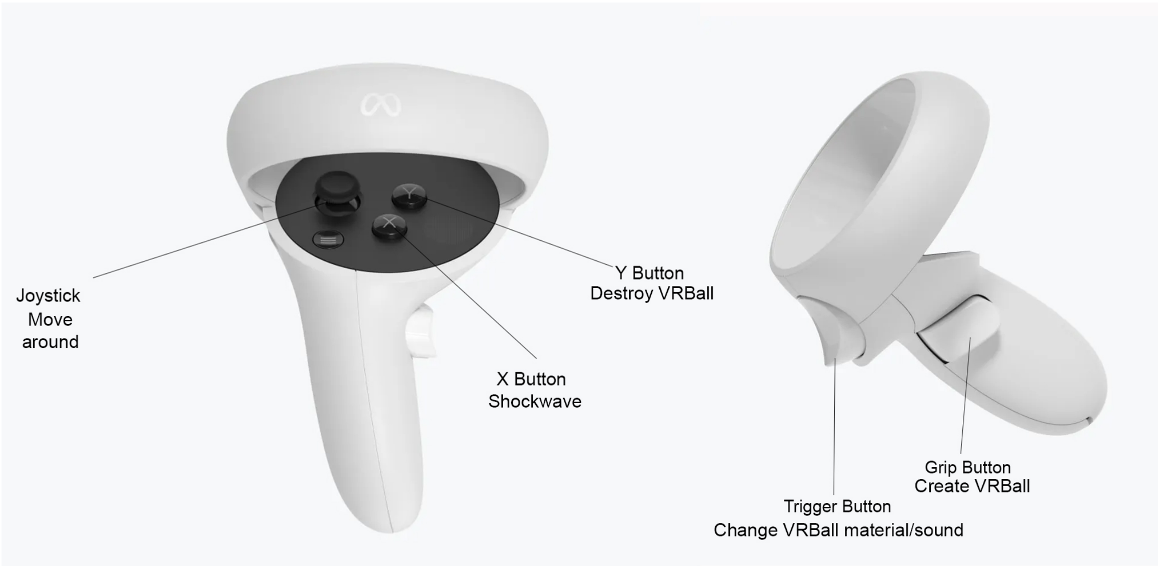


Figure 3.3: Quest 2 Controller and commands

of the movement until it hits an object, bouncing until the momentum is not enough to do so, disappearing 5 seconds after it is released from the user's hand.

Before throwing, the user can choose the material the VRBall should have. By clicking the trigger button, the VRBall's material changes. After throwing the VRBall, the chosen material will be selected for the next ball created, so that the user can throw a similar ball right away if he so desires. The different types of VRBalls are:

- **Regular Ball -** This ball has roughly the size and weight of a petanque ball and is the default ball material when a ball is created.

- **Heavier Ball -** Heavier than the Regular Ball, it has roughly the dimensions and weight of a bowling ball. This ball produces a rolling sound while rolling on the floor since its weight does not allow much bouncing.

- **Lighter Ball -** Lighter than the Regular Ball, it has roughly the dimensions and weight of a ping-pong ball. Its lightness makes it the most bouncy and also the one that can obtain the most spatial information.

Left Hand

The left hand contains more complexity, due to a higher number of possible controls. Once the VRBall is created, the user will have to move his hand to the desired place, in which the VRBall will stay for its entire lifespan, whether that is mid-air or near a surface. Just like the ones created on the right hand, by clicking the trigger button the user can change the properties of the VRBall, in this case, the outputted sound. There are 9 pre-defined sounds the user can choose from, cycling through them until the desired one is reached. These are everyday, familiar sounds that can easily be associated with different spaces, making the landmarking and cognitive mapping process more intuitive. One click will change the sound to the next one in queue, but a continuous click will trigger the option of a 10th sound: a custom voice input. The user can record his voice and, once placed, the ball will output the recorded segment of audio.

Contrary to the other type of VRBalls, once a ball with a specific sound is created and placed, the next ball created will produce the next sound in the queue, so that the user can reference someplace else with a different sound, optimizing the landmarking process. The only exception is when the voice input option is selected, in which case the queue does not advance, making the outputted sound the one that would be used if the custom voice input was not used. The following list includes all available sounds:

- Water flowing
- Fire crackling
- Grandfather Clock
- Wind Chimes
- Dog Barking
- Radio Static
- People Talking
- Frying Food
- Piano song
- Custom Voice Input

The user can also destroy balls, in the reverse order by which they were created. By pressing the Y Button twice on the Quest 2 controller (a confirmation request cue will play the first time the user presses the button), a user can destroy the most recent ball, which will then make the second-to-last ball created the next one that is allowed to be destroyed and so on. To turn the VRBalls on and off, the user can use the shockwave mechanic. By pressing the X Button on the controller, the balls' playback state will be changed to the opposite state (on to off or off to on). This is done sequentially, starting with the ball closest to the user and ending with the farthest one from where the shockwave was released.

There is no limit to the amount of VRBalls the user can create, both as landmarks or thrown balls, just like there is no obligation for these balls to be placed or thrown anywhere on the map, giving the user total freedom as to where and how to use these mechanics.

3.3.2 Environments

The prototype environment suffered some changes throughout the design process. The original first iteration environment was based on Andrade et al's testing environment [6], having clear start and finish points and clear passageways that lead to both these points. This was the approach followed in the second iteration of the environment design, this time with more rooms and different materials, in order to test the differences in sound according to materials and how these could influence exploration.

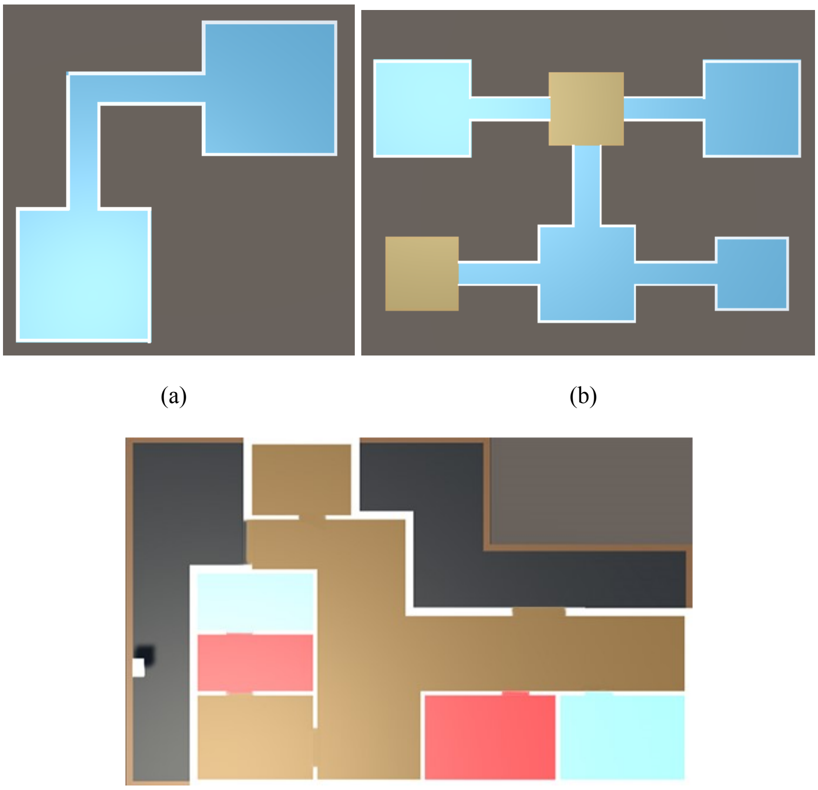
In the end, a decision was made to utilize another approach. Instead of relying on hallways and rooms, the choice was made to utilize a house-like environment, built with Blender, allowing for more complex geometries, in which the mapping process could be more familiar and less tedious, having a more dynamic space and allowing for a more obvious distribution of different rooms. These rooms have different sound configurations depending on the type of floor that is used, making them similar to specific house spaces, such as bathrooms or bedrooms. Figure 3.4 showcases the environments' design process.

There are also two extra components in these environments beyond the layout and the different rooms: a knocking sound on the starting point, simulating the front door, and an object producing the sound of birds, which is necessary in the process of the user study.

3.3.3 Sound

In order to better control the sound configurations and overall realism of the experience, Unity's audio system did not have the depth we needed, since it did not allow for a more broad configuration of both the sounds' effects and their mix. So a different sound engine was used: FMOD. This allowed for a better control of both the sounds' definitions and better mixing, while also allowing more complex sound settings and, consequently, a more realistic sound experience. The sound is fully spatialized, meaning 3D audio is used. This essentially simulates the way audio is perceived by the user as if it were being produced in the real world. As such, every action that has audio feedback will be heard differently depending on where the audio source is.

Whenever the user moves, the sound of steps will be heard. While moving, this sound will only stop if a wall is hit, in which case this hit will be accompanied by a specific sound, letting



(a) (b)

(c)

Figure 3.4: Environment Progress - (a) First Iteration, (b) Second Iteration, (c)Final Result

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the user know a wall is being hit. These hits are also accompanied by a haptic signal sent by the controllers, adding to the auditory feedback. This sound will also change according to each room's sound configuration.

Each room has a specific configuration, whether that includes more echo, higher or lower pitched sounds when surfaces are hit or general volume of sounds, those being the main sound variables. As such, when the user enters a room, the sound of his steps will change according to the sound configuration. This will also happen whenever a ball hits a surface in this room. The following list presents the types of rooms and their respective sound configurations, following the color scheme in Figure 3.4 (c):

- **Brown Room -** these rooms have both medium pitch, echo and volume. They mimic the sound of a bedroom or a hall, being that the large space has a little more echo than the other ones.
- **Red Room -** these rooms mimic the sound a small office or library would have, with lower echo and generally lesser volume. Sounds in these rooms are generally low and subtle.
- **Blue Room -** these rooms mimic the sounds of a bathroom, having a little more echo and the sounds being a little more high pitched as if the surfaces were tiles.

- **Black Room -** these rooms have a sound configuration that mimics the sounds one could hear in an outside space. There is no echo and the volume is a little lower since the sound has no surfaces to rebound on.

As a way to increase realism and to not have too much auditory information given to the user at once, the walls have an occlusion factor, lowering the sound and allowing the user to better filter which are the sounds coming from the same room as he is in.

There are audio cues every time a ball is created and when specific actions are performed, namely when changing configurations (changing materials and sound types) and changing the states of landmark VRBalls (turning them on or off and deleting them). These audio cues are essentially a voice indicating which action has been performed: for example, if a ball is created a voice will cue saying "Ball created" (in Portuguese). Some of these are also accompanied by a haptic signal. This way there is added accessibility and the user can know what actions are being performed.

3.4 Unity Asset

One of our objectives beyond the user study was the creation of an asset that could be used by others, which would allow not only for the free use of the finished product of this project but also for these tools to be validated in different contexts. As such, beyond the conclusion of the prototype, a package was built with some components that could be adapted to different projects.

The exported features were the creation and manipulation of VRBalls and a script that interacts with the them, allowing the sound produced by the thrown balls to be changed and make objects have a different identifiable sound. The scripts that deal with the FMOD features, bridging the FMOD and Unity3D projects, were also added to the package, along with the prefabs of the ball objects, one for throwing and the other for placing. As such, scripts that interact with our prototype's environment were not included, such as the ones that deal with logging positions and sounds of footsteps. The FMOD project used in the prototype is also different since there were tracks meant to only be used in the prototype. Finally, we also added voice cues in English, also maintaining the Portuguese cues, allowing for more diverse and international use.

Since these were developed with the 2.4 version of Unity's XR Interaction Toolkit package, which is not the one used for current Unity development for the Meta Quest 3, the integration in modern projects may be challenging if these use an incompatible Interaction Toolkit version. Also, because there are not many available open-source VR Unity projects, we could not test the asset in too many different environments, making it so that no larger projects are featured in the following list. Nonetheless, 3 different projects were used to test the features and the integration of the asset. These were:

- **Unity Learn's VR Environment[2] -** This is a simple environment that is part of Unity's free course on its VR feature and development, essentially a room with some objects. Its

[2] Available at `https://learn.unity.com/course/create-with-vr`

simplicity allows for a localized test with all the features, and the lack of built-in mechanics allows for all the features to be tested in a similar way to the prototype.

- **Unity's Beginner VR Escape Room** [3]**-** This environment is a small escape room game, designed by Unity. Although it is part of a small development course in which the objective is to develop this escape room, the final product is accessible, allowing us to test a more complex environment, where there are more interactions with its component, which makes the use of all the features more difficult.

- **Whisperer**[4] **-** This is a game developed by Meta to demonstrate their voice interaction SDK (software development kit). This is a more complex project, allowing us to understand the package's integration in a larger environment. The main use of voice allows for more commands to be added to the controllers, consequently allowing more features.

Some limitations were found in this process. Since not all projects utilize the FMOD engine, the sound integration is not always obvious since there needs to be a mix of both Unity and FMOD audio, which most of the time is not ideal. The collider interaction between both VRBalls and in-project objects can also become problematic, since some projects may not be prepared to deal with colliders that are not pre-programmed by the developers, and some VRBalls interactions may break the environment. In Whisperer's case, the hit of a VRBall on a vase broke the game, making it impossible for their use beyond landmarking.

Finally, this package and its associated documentation is available at the Unity Asset Store [5], and the source code is fully available at Github [6], allowing for any developer or researcher to access it and use it in any desired work, hopefully allowing for more accessible projects and new integrations of these tools.

[3] Available at `https://learn.unity.com/project/vr-beginner-the-escape-room`
[4] Available at `https://github.com/oculus-samples/voicesdk-samples-whisperer.git`
[5] Available at: `https://assetstore.unity.com/packages/tools/game-toolkits/vrballs-300820`
[6] Available at: `https://github.com/afchmbll/VRBalls`

Chapter 4

User Study

In order to investigate how these tools would be useful in VR and how blind users would fare with them and use their functionalities in a virtual environment, we conducted a user study where users were asked to perform an exploration and a navigation task inside three different virtual environments.

The main research questions we wanted to answer were:

- **Question 1 -** How can the use of tools improve and optimize exploration and navigation in virtual environments?

- **Question 2 -** Which VRBalls' features are the most useful in a VR environment?

Furthermore, this study was approved by the faculty's Ethics Commission Board.

Table 4.1: Participants

ID	Age	Gender	Technology Exp	Virtual Env. Exp	VR Exp	Amount of VR Exp
P1	40	F	6	5	Yes	2-10 times
P2	54	M	6	1	Yes	Up to 2 times
P3	29	M	6	6	Yes	Up to 2 times
P4	51	M	5	5	Yes	Up to 2 times
P5	50	F	7	1	No	-
P6	29	M	4	5	Yes	Up to 2 times
P7	21	M	7	7	No	-
P8	54	F	7	5	Yes	Up to 2 times
P9	38	M	6	4	Yes	Up to 2 times
P10	41	M	5	5	Yes	2-10 times
P11	37	M	7	7	Yes	2-10 times
P12	65	M	5	4	Yes	2-10 times
P13	36	M	6	5	Yes	2-10 times

4.1 Participants

We recruited 13 blind participants, 11 of them through the Raquel and Martin Sain Foundation [1] and the remaining 2 from connections established in previously performed studies. All participants were asked simple demographic questions, questions about their blindness (if they were totally blind or not and if so, for how long) and about their experience in interacting with technology, virtual environments and VR, being asked to rank that experience in a scale of 1 to 7, 1 being having no experience at all and 7 being very experienced, as seen on table 5.2;

4.2 Apparatus

We used the 3D prototype described above, running on a laptop with appropriate system graphics (NVIDIA GeForce GTX 1650), allowing for the study's conductor to change configurations if needed. The Quest 2 headset was connected to this laptop, along with a pair of headphones the participants were asked to use, in order to improve the audio experience, since the audio output of the Quest 2 HMD could be insufficient at times. These headphones, however, were not used in the tutorial section, so that the users could hear the study's conductor voice better while instructing them.

4.3 Methodology

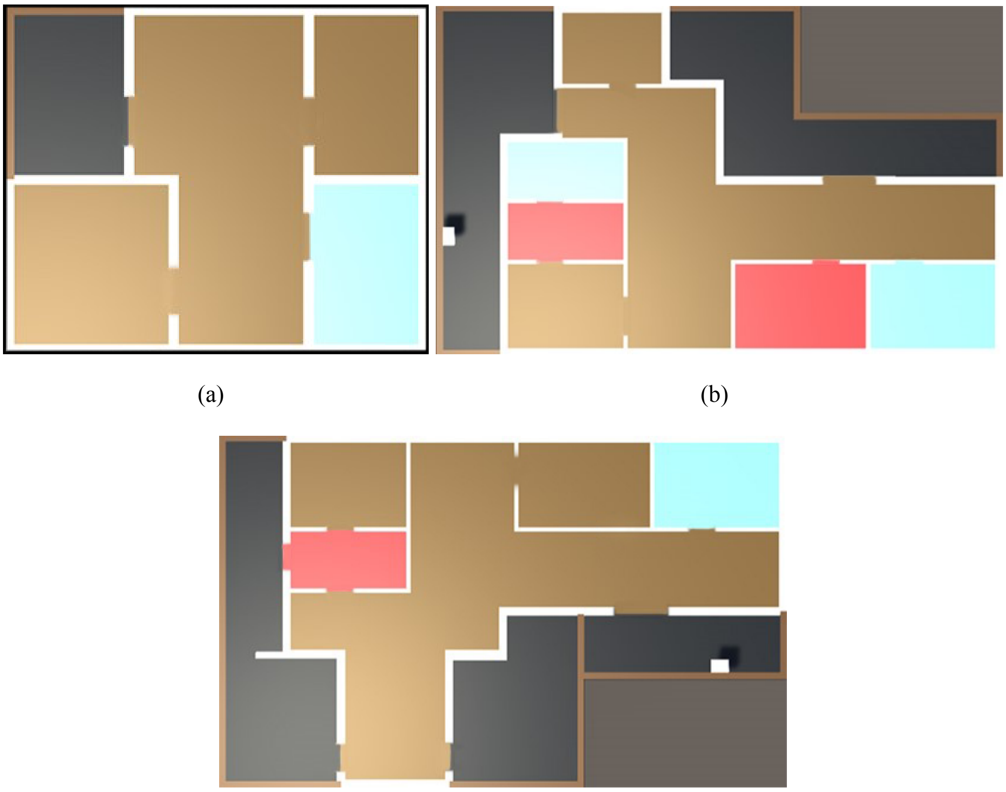
The user study consisted of three separate stages: doing the tasks with and without VRBalls and a semi-structured interview after these were completed. As a way to counterbalance the combinations of environment and use of VRBalls, some users started the study without using VRBalls and some started with them, just like some users started with the environment shown in Figure 4.1 (b) and others started with the environment shown in Figure 4.1 (c), making sure there was no specific advantage when starting with either of these combinations.

In the first two stages, there were three steps: the tutorial phase, the exploration task and the navigation task.

4.3.1 Environments

Beyond the tutorial environment, consisting of 4 rooms connected by a common room, the main testing environments were based in a real house, house Sidarus in Évora (Figure 4.2 (d), since it had a clear pathway between the end and beginning, with many different rooms through this path and enough dead ends that could allow for a slightly more difficult mapping, but not too many that could confuse the user beyond what could be acceptable. While one of these environments is a copy with some tweaks of the original house, the other one was created from scratch, following the logic of the first one, with the same number of rooms (9) and dead ends (2). These environments can be seen in Figure 4.1.

[1] `https://www.fundacao-sain.pt/`



(a) (b)

(c)

Figure 4.1: User Study Environments - (a) Tutorial Environment, (b) Test Environment 1, (c)Test Environment 2

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4.3.2 Tutorial

Before each exploration task, users performed a simple tutorial in order to understand the environment and tools' mechanics. The only exception was when users started the first task with the use of VRBalls, in which both tutorials needed to be condensed into a single tutorial. This tutorial was performed in the environment shown in Figure 4.1.

Starting without VRBalls, the users had the opportunity to test the movement dynamics, being able to walk through the environment, feel the contact with walls and hear the differences in footsteps' sound when entering different rooms, while also being able to explore the environment and find both different rooms and the starting point.

When the start was done with VRBalls, or the first section was completed, users tested all the mechanics of the use of these tools, being asked to throw balls to different locations in the environment, while also using different materials, and being asked to place landmarks in different places, to hear the sound differences depending on the distance to them and being asked to delete them and/or change their playback state through the shockwave function.

Only after understanding and being somewhat proficient in the use of these tools and mechanics was the user passed to the next step, the exploration task.

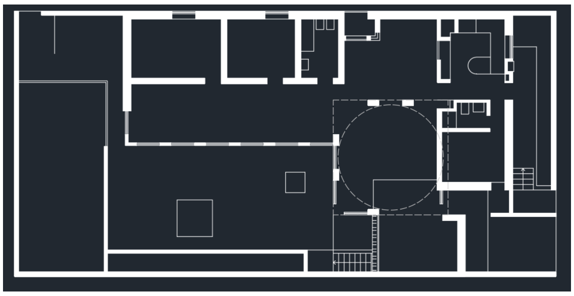


Figure 4.2: House Sidaurs, where Test Environment 1 is based from

4.3.3 Exploration Task

In order to understand how much information the users could collect and how they could cognitively map the environment with the use of the tools, we decided to ask users to perform an exploration task. This way we could access just how much of the space could better be understood with and without the tools, and how the users themselves perceived the environment they were in.

In the exploration task, users were invited to explore as much of the environment as possible as fast as they could, with or without VRBalls, depending on which phase they were in. They had 5 minutes to complete this task, at the end of which they were informed the time had ended through a buzzer inside the environment and were moved on to the next stage. In case they felt that the environment had been totally explored before the time ended, they had the freedom to move on to the next stage, asking the researcher as such.

After 5 (or fewer) minutes of exploring the environment, users were asked to describe the environment, namely what they believed the space's layout was, how many rooms there were and how many types of rooms there were. They were also asked to rate the easiness of the task on a scale of 1 to 7 (Single Ease Question - SEQ) [41].

4.3.4 Navigation Task

After completing the exploration task, users were sent to the navigation task. In both environments there was a cube volume, producing the sound of birds, which the user needed to get to as quickly as possible. Both sounds were equally distant from the starting point.

In order to put to the test exactly what knowledge was gathered during the exploration phase, and how each participant used it, we asked users to perform this navigation task. Using the information obtained in the previous stage, participants, in theory, could perform this task with more ease, letting us understand just how much information each participant took from the exploration and how they applied it to this task.

Even if the user did not find this sound on the exploration task, he had to explore the environment again in order to find it. Either way, after he reached the sound he had to return to the starting point as quickly as possible. This allowed us to understand if the user could effectively navigate the environment, even without finding the sounds on the first try. Afterward, the users were asked if they found anything else about the environment they wanted to add to the questions made at the end of the exploration task, and were also asked the SEQ.

If this task was performed with VRBalls, every landmark that was placed before stayed on the map unchanged, being turned on if the user left it off in the previous task, allowing the user to keep the references he created in the previous task and optimizing the navigation process, helping us understand how these can influence the cognitive mapping process.

4.3.5 Interview

Once all the tasks were completed, both with and without VRBalls, a structured interview followed. Here, we essentially wanted to understand the feedback the users had about both the tools themselves and the experience. They were asked:

- How using VRBalls affected their exploration capabilities;
- How using VRBalls as auditory landmarks affected their mental mapping capabilities;
- If VRBalls transmitted correctly the spatial dimensions of the virtual space;
- Advantages and disadvantages found in these of these tools;
- Which mechanics were the most useful;
- The contexts in which these tools may also be useful;
- Any additional feedback they had.

4.3.6 Procedure

The studies lasted about 75 minutes on average. The sessions were mainly conducted by the writer. The structure of the test was the following:

Introduction - The participants were greeted and informed of the research objectives and how the study would be conducted. Afterward, participants were asked to sign a consent form and fill in a demographics form. All audio was recorded after consent so that transcripts could be done later on. Participants were then introduced to the material to be used, being able to feel its dimensions and learning how the controllers worked. Participants were then assisted with wearing the Quest 2 headset.

Tasks - Participants were connected to the tutorial environment (see section 4.3.2). Depending on the environment/toolset combination for the first task, they stayed in it to learn only the movement and sound mechanics or to also learn the VRBalls mechanics, in which case this stage took longer. After showing proficiency in the use of these mechanics they were moved on to the exploration task and afterward, the navigation task, as described in earlier sections. Once the first round of tasks was completed, they were asked if a break was needed and moved on to the next round of tasks, repeating the process, excluding the tutorial section in case they had performed this task with the aid of VRBalls, as a way of not saturating the user. Once complete, the users were allowed to take off the headset and headphones and move on to the final stage of the study.

Final Interview - Once the tasks related to the virtual environment were completed, participants were asked questions as described in the previous section, giving feedback to the researcher on both their thoughts on the tools and the experience as a whole. They were thanked for their time and received a voucher as compensation.

4.3.7 Metrics and Analysis

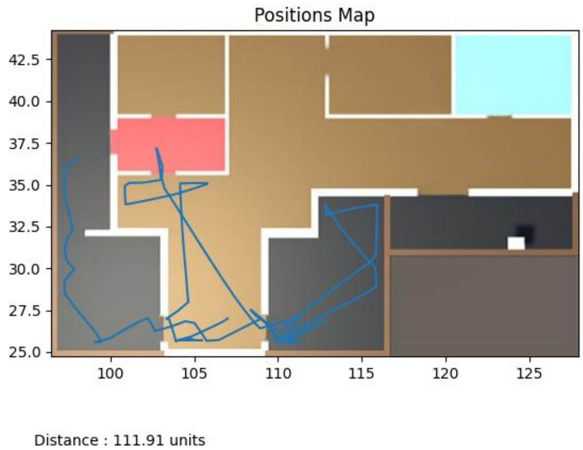
Our goal was to obtain as much information about the exploration as possible. In order to do so, participants' paths were recorded, along with the position of each VRBall created, through exported JSON files, and exported to images through a dedicated script. With these records we registered the distance traveled, the number of rooms each participant was in, and could perform a more specific analysis of each participant's task. Figure 4.3 showcases examples of these records.

In the moments where questions were asked, we wanted to understand the logic behind participants' actions and what their thoughts were relative to the tools and their possible uses. We wanted to obtain clear feedback from users, in order to understand their feelings during the experience more concisely and directly, in order to group their feedback relatively to different subjects of the tools' design, namely their ability to understand the surrounding space and how they could influence the user's cognitive mapping skills.

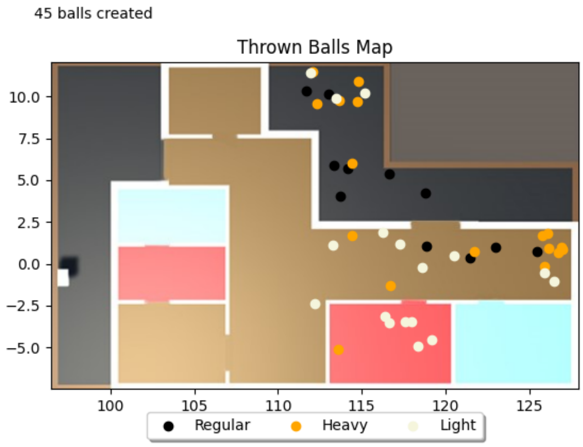
From the tasks inside the virtual environment we collected the amount of **Rooms Visited** in each task, along with and the amount of rooms where participants got stuck, and the **Amount of VRBalls Used** and their types. We also recorded the **Times** each user spent in the tasks and the **Distances** traveled in each task and. These values were also analyzed in order to evaluate the **Efficiency** of the exploration.

Users were also asked the **SEQ** [41], and to describe the environment. We compared this description with the actual path they performed as a way of establishing a metric that would allow us to quantify the differences between the path they traveled and the descriptions made (**Room Perception**). It is important to note that these descriptions and the interviews performed later during the session were transcribed and analyzed post-study. From these transcriptions, we also obtained qualitative data from the participants' responses.

With all these data, we were able to analyze and produce a series of conclusions about the study sessions and the project as a whole.



(a)



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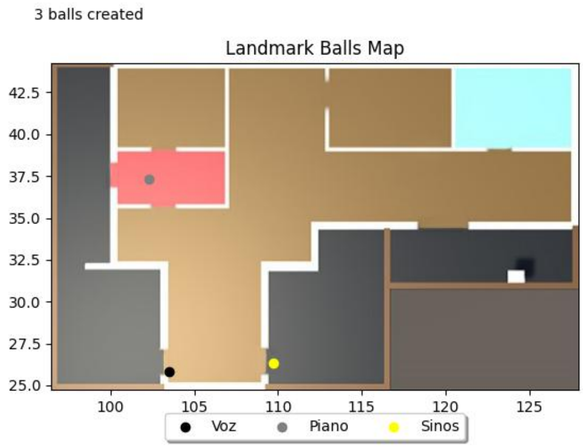

(c)

Figure 4.3: Collected Graphics - (a) User's Path, (b) Origin of thrown VRBalls, (c)Location of placed VRBalls

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Chapter 5

Results

The data collected from the various study sessions can be separated into quantitative and qualitative data. This data includes every metric related to both the exploration and navigation tasks and the interview, along with the questions and feedback given throughout the entirety of the study session, as described in the previous section.

5.1 Results from Quantitative Data

This data was mostly obtained through Unity's logs and calculations performed afterward. The users' path was run through a Python script which allowed us to see the full path in a graphic, and such was also the case with both thrown and landmark VRBalls. Through these graphics, programmed Unity logs and feedback given by the users the results we found were the following:

5.1.1 Rooms Visited

Both environments were similar to one another, both in the number of rooms and in their space disposition's logic. Even though the tasks were performed with a counterbalanced order, meaning that every possible combination of spaces/modality was cycled through every participant as much as possible in order to make sure no environment brought better results.

We found that the averages for amount of rooms visited were very close, but there is a slight difference in the amount of rooms found on average in the navigation task with and without VRBalls. While the average amount of rooms visited (R) in the exploration task was R = 3,08 (σ = 0,95 and σ = 1,11, without and with VRBalls respectively), on the navigation task this value is R = 2,92 (σ = 0,86) without VRBalls and R = 3 (σ = 1,15) with them, as seen in Table 5.1. We accounted for the main room in these calculations, meaning every participant at least passed through one room. The total standard deviation was σ(R) = 0,99.

Out of the 9 available rooms in each environment, participants found at best 6 in both, accounting for the total amount of rooms found in both tasks. On average, participants found 4 rooms in total per environment. After all the user studies, no room was left unexplored. We analyzed the number of new rooms found in the second task in order to understand if the use of VRBalls was equivalent to more rooms being found in the second round, but no conclusive result came out of

Table 5.1: Average Amount of Rooms found

	Without VRBalls	With VRBalls
Exploration Task	3,08	3,08
Navigation Task	2,92	3

it. Excluding P5, who did not use any VRBalls in any task, 5 participants found more rooms using VRBalls, 5 other participants found the same amount of rooms and 2 found less rooms, as seen in Figure 5.1. From the ones who found more rooms, one participant found 2 more, but the remaining found only 1 more. This leads us to conclude that the exploration experience's results were not worsened by using the tools.

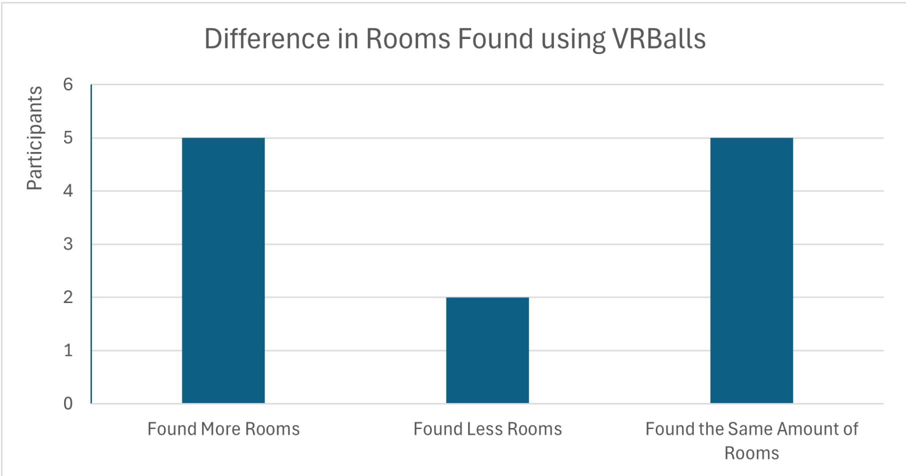

Figure 5.1: Difference in Rooms Found using VRBalls by Participant

Participants also found themselves often stuck in determined rooms. We define stuck as passing through the same point inside a room multiple times with the goal of finding the exit and not being able to. Since most passageways were the same size, these could be either smaller rooms or even the main room, which some participants could not get out of. An example of this is shown in Figure 5.2, showing a task where the participant (P6) got stuck in a room.

Every participant found himself to be stuck in a room at some point, which, depending on the participant's style of exploration, affected the experience as a whole (a quicker participant could get stuck but also explore his way out more quickly). We found that on average participants were stuck in fewer rooms when given the option to explore with VRBalls. Given that most amount of times participants got stuck in rooms was 2 (with the least being 0), the average rooms (AS) per task were AS = 1,15 and AS = 0,81 (σ = 0,73 in both), without and with the use of tools respectively.

In this matter, we also found that there was not a specific room in which participants got stuck more often. Some participants were stuck in the rooms directly next to the starting point, while others only found themselves stuck after walking towards a more distant one. We found no pattern

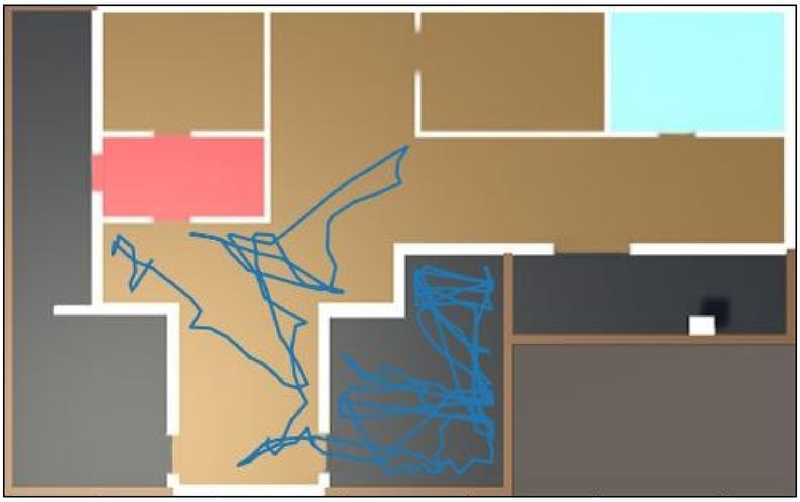

Figure 5.2: An example of a participant's trajectory when stuck in a room

that led users to be stuck more often.

5.1.2 Amount of Balls Used

It is important to note that not all participants used the tools to their full extent, and we also took that into account. Some participants only used the throwing feature, while others only used the landmarking feature and one participant did not even feel the need to use VRBalls. The distribution was the following (as can also be seen in Table 5.2):

Table 5.2: Strategies Used by Participant

Strategy	Participants	Count
Only threw VRBalls	P2, P11	2
Only placed VRBalls	P4, P7, P8, P9	4
Did not use VRBalls	P5	1
Threw and placed VRBalls	P1, P3, P10, P12, P13	5

Given that not every participant used all of VRBalls' features, the amount of VRBalls used by every participant is variable: for example, while P5 used no VRBalls, P3 assumed a strategy of using as many balls as possible randomly, throwing about 300 VRBalls and placing 89 in the exploration task. As such we measured the amount of VRBalls thrown by each participant and each type of ball.

Starting with the landmark-oriented VRBalls, the average amount of balls placed (BP) by user was BP = 10,28, BP = 3,83 excluding P3's results, which were much different from the others (79 more VRBalls placed, compared to the second highest amount, which was 10). Only including those who actually placed VRBalls, that number is BP = 13,5 with P3 and BP = 5,11 without

P3. We also found that there was no preferred sound, as the sum of all different balls by sound is generally similar, ranging from 12 to 15, except for the voice input VRBalls, which were used very little.

Given that the pool of users who threw VRBalls is smaller (5 participants did not throw VRBalls at all), and factoring the results from P3 in the exploration task (368 VRBalls were thrown in the exploration task), the average amount of balls thrown (BT) by each user was BT = 7,83 in the first task (BT = 35,54 if accounting for P3's throws) and BT = 6,92 in the second task. There was no clear preference in choice of material: excluding once more P3's results, the most thrown VRBalls were the lightest (average of BT = 6,92) and the least thrown were the heaviest (average of BT = 4).

Participants who threw VRBalls mostly used the mechanic in both tasks, with cases of participants throwing more VRBalls and participants throwing fewer, compared to the first task. There was no conclusive difference in results from both cases. Participants who placed VRBalls generally placed them in the first task only (7 out of 10), while the remaining participants only placed a few more. Once more we found no conclusive difference in terms of results of strategies.

We also compared how using more or less VRBalls influenced the users's performance, excluding the outlier P3, who threw and placed a significantly larger number of VRBalls compared to the remaining users.

5.1.3 Times

Users had 5 minutes to explore as much of the environment as they could in the exploration tasks, or, in case they thought the environment had been fully explored, could stop the timer and end the task earlier. In the navigation task, had 5 minutes to find a sound located in the environment and go back to the starting point.

No participant chose to end the first task earlier, in any modality (with or without the use of VRBalls). As such in every exploration task the timer ran all the way to zero. In some cases the birds were found in this task, mainly in the case of P9, who found them in the second exploration task, using VRBalls, and P10, who found them in both modalities.

No participant found the birds in both exploration and navigation tasks in succession. In the navigation tasks, most participants could not find the birds, with the exception of P2, P5 and P9, each with a time(T) of T=78s, T=278s and T=126s respectively. None of these participants could find their way back to the starting point, although P2's path after finding the birds came relatively close to the starting point.

5.1.4 Distances

Participants' distances were measured through the distance between the coordinates in which they were every second. These distances(D) ranged from D=79,09m (meters) to D=282,25m and varied depending on the task performed and modality.

Table 5.3: Average Distances per Task

Tasks	General	Throwing	Placing	Throwing & Placing
Exploration Task without VRBalls	177,6	-	-	-
Exploration Task with VRBalls	144,4	232,5	144,0	126,1
Navigation Task without VRBalls	190,2	-	-	-
Navigation Task with VRBalls	167,8	222,1	170,9	153,2

As seen in Table 5.3, we found that users had an average distance of D = 177,6m and D = 140,4m in the exploration tasks without VRBalls and with VRBalls respectively. Regarding the navigation task, the average distance was D = 190,2m and D = 167,8m, again without and with VRBalls respectively. This may suggest that the average distance traveled is lower when using VRBalls.

We also understood that the users who went the longest distances when using VRBalls were the ones who only threw VRBalls, averaging D = 232,5m and D = 222,1m in the different tasks, and the ones who performed the shortest distances were the ones who utilized both main features of VRBalls, averaging D = 126,1m and 153,2m.

Since users found, on average, the same amount of rooms in the exploration task, both with VRBalls and without them, these results can suggest that users may be more strategic, spending more time thinking about the best way to use the tools, which could bring them more knowledge of the space, but also decrease the amount of space traveled through. This could also be valid for the navigation task, raising the hypothesis that the use of VRBalls can reduce the distance travelled, but make the exploration more productive.

5.1.5 Efficiency in exploration

Analyzing the efficiency is participants' explorations allows us to better understand the results of the participants' results through a deeper analysis of their explorations. In this metric, we compared the total amount of rooms found with the amount of times they found themselves stuck in a room. Our goal here was to determine how exploring the efficiency in the fulfilling of the tasks' objectives could lead us to further conclusions on who had better results, and if the exploration with VRBalls resulted in better performances. Comparing these two values lets us understand the efficiency in each participant's exploration: for example, a participant who finds more rooms and is stuck more often is a more proactive explorer, while a participant who finds fewer rooms but is stuck more often has more difficulty in the exploration.

We decided to create a matrix with the different styles of exploration according to determined values. Since the most amount of rooms found was 6, and the median value was 3, we decided to divide the amount of rooms explored between 3 or less and more than 3, dividing the amount of results as equally as possible between the two fields. Participants were stuck in rooms no more than 2 times, and the median value was 1. As such, we decided to divide participants between being stuck 2 times and being stuck less than 2 times. Since the participants who found the birds in the first task did not find them in the second task, we decided to apply this metric to every task, since there was an exploration component in all of them.

Table 5.4 and Figure 5.3 shows the various exploration styles:

Table 5.4: Different Efficiencies

	Found Less Rooms (<=3)	**Found More Rooms (>3)**
Got Stuck Less (<2)	Limited	Precise
Got Stuck More (2)	Erratic	Intense

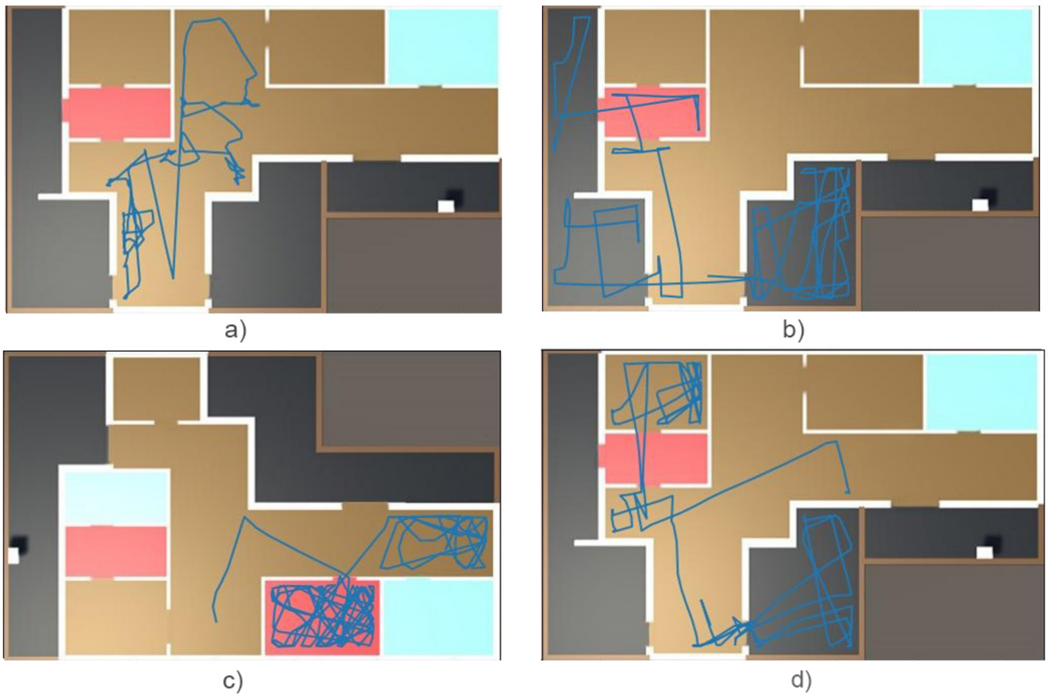

Figure 5.3: Different Efficiencies Visualized: a) Limited, b) Precise, c) Erratic, d) Intense

Limited explorations imply a small amount of rooms are found, but participants also do not get stuck so often. We applied this metric to every task performed by the users. Users with an Erratic approach are the least efficient since they find fewer rooms and get stuck more often, as seen in Figure 5.3, where the participant got stuck twice and did not find many rooms. On the other hand, users with a Precise approach find more rooms and get stuck less often, allowing for a better exploration in theory. Intense explorations lead to more rooms found but more difficulty in finding, making it the style of users who have the most dynamic approach. We applied this metric to every task performed by the users. Table 5.5 showcases our findings.

As seen, the use of VRBalls did not influence the efficiency of the users' exploration in an effective way. In a general way, while for some users the efficiency was improved, for others the opposite can be observed. Some users had different exploration styles in all tasks while others did

Table 5.5: Efficiency Results

Type	Total	Without VRBalls	With VRBalls
Limited	28	12	16
Erratic	9	6	3
Precise	10	5	5
Intense	5	3	2

not change, even with the use of the tools. These inconclusive results lead us to observe that the difference between values is not significant enough to draw conclusions about the effectiveness of the tools in the efficiency of the exploration, which may be due to the difficulty of the task itself and the complexity of the environments participants were asked to explore.

5.1.6 SEQ

After every task, participants were asked to rate the easiness of the task on a scale of 1 to 7, 1 being ”very hard” and 7 being ”very easy”, a metric that originated from Sauro et al.’s work [41]. On average, participants found that doing tasks with the use of VRBalls was slightly easier, as seen in Table 5.6. The navigation task was considered harder than the exploration task, as can also be seen. Overall the differences in the use of VRBalls and the lack of them are not significant enough to draw any major conclusions.

However, larger differences can be seen in the average answer from the groups that did not use all of VRBalls’ features. The task’s easiness was considered the highest by those who did not throw any VRBalls, and lowest by those who used all of the available mechanics. This could mean that the approach of using VRBalls both ways may not be the most efficient one. P5’s SEQ answer to the tasks performed with VRBalls was 7, but since there was no use of the tools, and since that was the only case, it is not a comparable result.

Table 5.6: Average SEQ

Tasks	General	Throwing	Placing	Throwing & Placing
Exploration Task without VRBalls	4,2	-	-	-
Exploration Task with VRBalls	4,3	5	5,25	3
Navigation Task without VRBalls	3,5	-	-	-
Navigation Task with VRBalls	3,7	3,5	5	2,6

5.1.7 Room Perception

Room perception measures how accurate the participants’ descriptions of the space were. By room perception (P) we measure the amount of rooms the participants were in (Ri) compared to the number of rooms they described (Rd). Essentially we subtract the number of rooms described from the number of rooms found, resulting in $P = Ri - Rd$. If P is positive, then the rooms where the participant was in were not identified. If D is negative the amount of rooms described is larger than the amount of rooms the participant went through, and if P=0 then the description matched the path they took.

Only 7 out of the 52 answers resulted in a negative Room Perception, while only 13 descriptions matched the paths taken. In order to avoid errors in the averages calculations (a negative number could skew the results in a false direction), the averages were calculated as if all numbers were positive, in order to maintain the values and not have negative numbers misrepresent the actual cases.

Following this logic, the total average room perception was P = 1,09. This would indicate that, on average, participants mostly understood the environments they were exploring, given that the average amount of rooms found was 4. The use of VRBalls was also relevant, in such a way that the average room perception is smaller when using them to explore. As seen in Table 5.7, P is smaller or equal in every case when VRBalls are being used. However, given that this difference is marginal, we cannot draw clear conclusions from this metric.

Table 5.7: Average Room Perception

Tasks	General	Throwing	Placing	Throwing & Placing
Exploration Task without VRBalls	1,3	-	-	-
Exploration Task with VRBalls	1	1	1,25	1,3
Navigation Task without VRBalls	1,2	-	-	-
Navigation Task with VRBalls	0,9	0,5	1,25	1

5.2 Results from Qualitative Data

From the interviews, we obtained subjective feedback, which helped us understand the participants' opinions about the tools and the study in its entirety, along with how they believed VRBalls influenced their experience. Some thoughts about what we saw in the paths and strategies the users used are also included in this section.

5.2.1 VRBalls' influence in the experience

Participants in general felt that their exploration was influenced by the use of VRBalls, although not always in a positive or tangible way. It was mentioned by more than one participant that using VRBalls to reference locations helped them in their exploration.

"Without those [VRBalls] markings it is very hard, one ends up getting lost in the space" - P4.

"I gained more autonomy with the sounds(...), the balls we can create. And it helps a lot." - P10.

It was also mentioned that, although using VRBalls influenced their exploration, they still felt lost, as was the case with P13.

"I felt that I was influenced, more by those that could be placed in determined places, but not that it eased that much my space navigation capability (...) I still felt lost" - P13.

It is worth noting that participants' strategies varied and, while some uses clearly showed that the use of the tools brought them a different perspective on the exploration process, the influence was not always in a positive way. The use of VRBalls did not always translate to better results and different explorations of the space, having participants stuck in rooms as much as when there was no use of VRBalls.

Most participants also mentioned that their mental mapping capabilities were also influenced by the use of the tools, with the participants mentioning that the placing of VRBalls was a strategy of marking the places already visited and creating mental references.

"When I was in a place, I placed a ball and I could know if I had already been in that place" - P6.

"It was really helpful because with those sounds we can know 'I placed this sound here so I cannot go that way'" - P10.

Participants also agreed that VRBalls transmitted a precise image of the space's dimensions, although not in a consistent way. Participants such as P2 and P4 mentioned that they were focused on the objectives of the task and did not focus on the dimensions of the space itself, and as such could not answer with certainty.

"I did not think about it, distances or anything" - P2.

P2 also suggested that by using the tools in a better way maybe the answer could be different, a thought shared by P12:

"(...)emphasizing that I may have not done the exploration in the most correct way, but honestly when I sent the balls I did not feel that they were making it easier (...)" - P12.

P4 mentioned that the dimensions of the space were obtained through the sound of steps and not through the sound of the throws' rebounds. P8 did not throw VRBalls, but mentioned that with time and training would want to explore them. P9 did not use them, but justified it by saying that the information they transmitted was not very clear and useful and, as such, did not feel the need to use them.

"The more useful were the balls of creating sounds(...) because always hitting the walls with the balls makes it seem that the space is always the same." - P9

5.2.2 VRBalls' mechanics

Most participants found no disadvantages in the tools. P13 mentioned that having too many landmarks could create a confusing amount of sound and that the sounds of the thrown VRBalls were somewhat confusing as well, not as precise as what would be appreciated, leading to the conclusion that they had no real advantage.

"(...) Depending on the amount of balls created, a confusing sound environment can be created,(...) I thought the sound of the light, medium and heavy balls was somewhat diffuse (...) and I did not see many advantages...or none." - P13.

In terms of advantages, it was mentioned that the landmark VRBalls were very useful, in the sense that these tools guaranteed a stable sound source, that in turn guaranteed a reference and orientation point. This was the most consensual advantage of these tools.

"The advantage of the balls is having a location and orientation point." - P4

P8, for example, also mentioned that with more time these tools could be better understood and, in turn, more advantages could be found. Participants also mentioned that the handling of the tools was fun and a good leisure activity.

Participants mostly agreed that, beyond some features of the environment that aided in exploration, the tools in themselves were recognized as useful. The preferred mechanics were the core ones: throwing and placing. Most participants recognized that the placing of VRBalls was very useful, although some participants also recognized that the throwing of VRBalls made more sense to them.

"Most useful were the ones of creating sounds" - P9

"It was the one [mechanic] of the balls' sounds, being able to place them in a certain point..." - P12

"Throwing the ball was the most advantageous [mechanic]" - P11

Not all participants used the full range of features available in them. In this case the participant was asked why they did not feel the need to use one or another solution, in case they omitted the throwing or placing of VRBalls or their answers did not explain this. In P5's case, the participant was asked the reasoning of the choice of not using VRBalls at all, answering that there was some confusion that was not clarified about the moment of usage of the VRBalls, and that the integration of the tools in the task was not obvious. This participant performed the tutorial stage with no problems.

Participants like P11 found that using VRBalls as landmarks in his run of tasks was not as useful as throwing them, confirming when asked that there was no necessity felt for placing VRBalls. P2 also did not use these mechanics but because there was some confusion in how to use them in a practical scenario.

5.2.3 Uses and suggestions

Participants were also asked in which contexts they found possible future uses for the tools. "Games" was an answer given by more than one participant. Other answers included training environments, such as learning spaces beforehand and training Orientation and Mobility (O&M). The use of the tools in open large spaces, as a way of referencing the different parts of the space and in an environment where there is a need to track the path already followed, referencing the already visited places.

"In game's tools (...). In the creation of games, in the study/training of orientation and mobility, of laterality (where people need to learn to distinguish where is the left, where is the right)..." - P5

Participants also made some suggestions about the environment and the accessibility of the experience itself. P4 and P13 suggested that entrances should be marked with specific sounds, as a way of optimizing the amount of time of exploration, mentioning that with some more references, they would not hit as many walls and, as such, would not waste as much time in finding the door.

"(...) when I'm close to the door it should play a little sound(...). This would help the user." - P4

Participants also described the logic process behind their actions in the various tasks, from the way they perceived the environment to even commenting on other strategies they realized that could be useful. P5 commented that the tools were a way of relieving stress and P13 did not quite understand the reasoning for the study.

5.2.4 Strategies

Users chose different strategies throughout the exploration process. Without the use of VRBalls participants mostly walked around the environment, hitting the walls and (for some) trying to notice differences in the sound of their steps.

Although not always the case, the approach changed with the use of VRBalls. There was not a preferred strategy, although some points were common. It is important to note that no strategy was distinguished as being the most efficient one. Users who threw VRBalls mostly threw them near walls, possibly to distinguish distances. There were also instances of VRBalls being thrown in the center of rooms and around the user, particularly by P11, who showed the most proficiency in their use. We saw no preference in terms of weight and size.

The use of VRBalls to create references was the most used feature. Participants who understood this mechanic better and used it more proficiently either placed balls in specific points of rooms (center or entrances) or placed them along the path they were in. No strategy brought out a significantly better performance.

Chapter 6

Discussion

We investigated how the use of the developed acoustic tools could influence exploration and navigation in virtual environments. The study's results suggest that our approach did not have the positive results we intended, but the users' feedback indicates that there is room for these tools in the accessibility field. In this section, we will discuss the answers to our research questions by summarizing the main results we obtained and the lessons learned from this analysis.

RQ1 - How can the use of tools improve and optimize exploration and navigation in virtual environments?

Our quantitative analysis revealed that using VRBalls as accessibility tools suggested no clear advantage in their use while exploring the space. Participants traveled on average larger distances without using VRBalls and the use of the tools did not influence the eficiency of their exploration in a tangible and positive way. However, the SEQ results show that, on average, participants found the tasks performed with VRBalls easier, which, along with the fact that, on average, participants found more rooms on the navigation task using VRBalls and had a better, although marginal, average perception on both tasks, leads us to believe that the use of VRBalls could be useful in exploration settings, but the data we recovered is not enough to produce definitive conclusions. We also found no difference between the average total amount of rooms found per environment.

The low results might be because users had to use tools they had no experience with, beyond the tutorial stage, in a practical setting with little to no aid. Given that more than half the participants had never tried VR or had tried it less than 2 times, it is reasonable to assume that more experience could also lead to better results. Along with the difficulty of the environments, it may be reasonable to assume that the potential of the tools cannot be discarded.

The qualitative analysis suggests that, in general, participants actually value the use of VRBalls and find that their exploration can be improved by using VRBalls, mentioning that referencing places they had already gone through makes the exploration process easier, along with the fact that being able to utilize different sounds makes the mapping process more straight forward, leading us to believe that referencing the space is the most useful and needed mechanic.

RQ2 - Which VRBalls' features are the most useful in a VR environment?

According to users' answers, using VRBalls as landmarks is the most popular feature. This mechanic allowed them to reference the space and have an easier time mapping and traveling through it. Only 3 users did not use this mechanic, making it the most utilized overall. Participants who only used these features and others related to it found the tasks easier overall (4 participants in 13). Beyond this, participants who used them found on average more rooms in the second task than in the first, indicating that there is a referencing aid.

However, the rest of the qualitative data does not indicate their usefulness. The average distances while using the tools are smaller than the average distances traveled without them, the room perception does not give any conclusive arguments relative to this and the amount of rooms found varied between participants, with the average number of total rooms found with the use of the tools being about the same as the ones found without them.

6.1 Main Takeaways

Beyond the answers to our research questions, we also got some takeaways and lessons learned from the study as a whole worth mentioning.

Well-developed main mechanics may reduce the impact of the use of external tools. Not every participant felt the need to use the tools provided. Yet almost every participant mentioned that the audio feedback, both from steps and collisions, was helpful in the exploration process and in referencing themselves to the space around them.

Although the task they were given was not easy, and the results showed this, the similarity of the results obtained with and without the tools may suggest that if there are a few elements that make the experience just a little more accessible, a large set of accessibility tools may not bring as many advantages, compared to an exploration in an already accessible environment, with sound elements all-around.

Passageways should be marked or easy to recognize for a better experience. Participants found themselves stuck in a room more than once. The usual strategy in this case was hitting walls, sometimes indiscriminately due to frustration, which made them waste time. More than one participant mentioned that entrances should be referenced in such a way that when a user is near them he could know where that passageway is and make the process of entering different rooms easier. No participant mentioned the actual size of the passageways, but the correct future research path goes through increasing the size of these passageways, to make them easy to find, no matter the room.

Although one of the inspirations for the use of these tools was exactly the referencing of doorways and entrances [18], only some participants made the logical leap of using the tools to reference passageways, and even then there were some complaints about the overall ease of getting to those doors, leading us to conclude that our configuration of passageways was not the best. Allowing users to have a clear reference of a passageway helps the fluidity of the exploration and makes the overall environment simpler to travel through.

More sound distinction between the elements helps. In this line of thought, the clearer the reference, the easier it is for participants to have a better experience. More than one participant mentioned that the differences in sound inside the rooms, collisions and landmarks were helpful. One participant also mentioned (justifying why he only felt the need to place VRBalls) that throwing VRBalls did not help in his exploration because the sound had no relevant difference beyond volume, and, as such, did not prove to be an effective exploration tool.

By having these differences in sound, users were able to identify different spaces and distinguish references. This begs makes us question if users would be able to have better results, with or without the tools if every element, be it walls, floors, etc., had a specific sound. Users mentioned that more sounds referencing passageways would be useful, so we believe that having more sounds to identify more objects and places could make the exploration process easier.

In our approach, every VRBall the user threw would play the same sound, independent of the object it hit, with some tweaks in key variables, such as reverb, pitch and volume, altering it to some extent but not having a very high ceiling for different sounds. Given that the only objects available in the environment were walls, we felt that there was not much need for large differences in sound, but implementing objects with specific sounds in different spaces could be a helpful addition to the exploration process.

6.2 Limitations

From the results obtained, we also took away a set of limitations that should be studied in future iterations of this project, in order for it to be improved and produce clearer and more conclusive results.

The tasks were too hard. Participants performed their tasks in environments with 9 rooms. Of these 9 rooms, the best case scenario was when a participant found 5 rooms, the main one plus 4, with a total of 6 in the full environment after both tasks. Beyond the number of rooms found, in the 26 performed navigation tasks, the birds were found in only 4 of them, while no participant made it back to the starting point - that is a 15% success rate in finding the birds and 0% success rate in returning to the starting point afterward. Given that the use of tools did not worsen the results compared to not using them, we present the hypothesis that the difficulty of the task itself was the biggest challenge, and not using the tools themselves.

We hypothesized that participants needed to have more intricate rooms, to showcase the use of the tools, and that fewer rooms would result in too simple explorations, making the results not significant. Environments with a complexity not too different from the ones in Thøgersen et al's work [45], or the ones in Andrade et al's work [6] could be a target for tasks executed in future work.

The space in itself was not easy to travel through. Although the main room was large and no participant had difficulty walking through it, every participant found himself unable to leave at least one room in at least one of the tasks. Even with the use of VRBalls, participants often found that leaving rooms was the hardest part of the challenge, which also led to frustration and time lost in trying to find the exit instead of exploring. As such, we can suggest that larger passageways could have made the task easier and provide better results. As suggested by some participants, using a referencing sound indicating the presence of passageways and their delimitation could have also been a way of making the task easier and more dynamic.

Not all features were necessary. Users had a series of mechanics available to them. Most of these mechanics were, however, not used in their entirety. No user used the entire set of mechanics in their tasks. The shockwave feature was mostly never touched, and few users felt the need to record their voices. Since some of them skipped the use of entire hands (choosing to not throw or place VRBalls), we could say that some features were not entirely necessary, which could have made for a shorter tutorial and given the participant less of an information overload, which might be the cause of choices such as only using one mechanic (for example throwing) and discarding the other.

Another alternative to this could be performing more tasks with fewer features each time, giving the user time to adapt to each mechanic and to be able to choose only some actions at a time, which could have possibly given them better results.

A small user pool. We recruited 13 participants, mostly through the Raquel and Martin Sain Foundation. These participants provided us their feedback and opinions, which were very helpful in allowing us to understand the tools' potential and use cases. We also felt that more feedback could have helped us to better understand the potential of the tools, and introduce more questions and subjects to provide a deeper analysis on the results obtained.

A larger user pool could have possibly given us more perspectives on the tools' flaws and different or better strategies that could lead to better results. We hypothesized that a pool of users the size of the one presented could be enough for clear results, but future research could take into account the use of more test subjects, leading to a deeper analysis of the tools' use.

Chapter 7

Conclusion

In this study, we contributed with a new perspective on accessibility in virtual environments, in order to provide more accessible experiences to blind users, and allow them to use acoustic tools in such a way that both their orientation and exploration skills could be improved as much as possible, while also giving them the ability to freely use these tools in such a way that there would be no limit or constraint in neither the amount, location and type of mechanics and features to be used.

Through a user study performed with 13 blind users, we were able to test a prototype of these tools, which allowed us to not only evaluate how these users would fare with the use of VRBalls in a practical setting, but also how the tools themselves could be useful in an exploration and navigation assessment in an environment similar to a physical building floor. We also tested these tools in different environments, not made by the research team, in order to understand how the implementation of these tools in different contexts would work.

The results ultimately showed that our approach did not have the outcome we predicted. Although the use of these tools improved some parts of the process, results showed that when there were no tools being used, most participants could explore the environment just as well as when they had no tools, even if some participants actually had better results using them. Since most of the results proved to be inconclusive on the matter of which alternative is better for a more accessible exploration, we can not conclude with certainty that our tools can be used to improve accessibility in a straightforward way. We can, however, present an alternative worth studying, since some performances did prove to improve with the use of our tools.

Nonetheless, participants said that the tools were helpful, and that their features aided them in exploring and traveling the environment in a different way, which makes us believe that with future work, these tools could be implemented in such a way that both opinions and results could paint a more positive picture.

7.1 Future Work

Regarding future work, many fronts could be taken. VRBalls could be studied with users once more, but this time in different environments with more populated rooms in terms of objects, more obvious passageways and more sessions, to determine if more use of the tools could improve result over time. Features could also be tested separately to determine if in fact the use of VRBalls as landmarks is their most useful mechanic.

These tools could also be tested by users in different pre-made environments, i.e. other VR contexts such as games and other open in source projects, allowing us to see how they would fare with the tools in unexpected situations, both by them and by the research team. Beyond this, the tools' design could also be updated to be flexible in any context, programming them so that they can be used in any environment without any specific configurations and rigid requirements necessary, allowing for true accessibility and diversity in their ability to be used.

In a more general plane, these tools could be adapted to also be used in 2D environments, allowing for blind players to use them in non-immersive VR environments, and bring the accessibility mechanics explored to those spaces. Not only to 2D, these tools could be adapted to work in augmented reality (AR), allowing for users to apply these tools to the real world, bringing these tools to the physical space and giving them further utility outside the virtual environment.

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