

# **Echolocation as a Means for People with Visual Impairment to Acquire Spatial Knowledge of Virtual Space**

Ronny Xavier Andrade Parra

<https://orcid.org/0000-0003-2625-1572>

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*This work is dedicated to my parents, whose foresight in enrolling me to  
English school is what has brought me here.*



# Abstract

The creation of virtual worlds started with the very first computers in the sixties and has been deeply intertwined with the development of digital games. As computer hardware becomes more powerful, these virtual worlds and the digital games that are developed within them become ever more realistic. Information in virtual worlds is usually conveyed visually. For this reason, the digital games that occur within virtual worlds are commonly referred to as videogames. However, this reliance on the visual sense means that these worlds are mostly inaccessible for people with visual impairments.

Although the challenges of making virtual worlds accessible to people with visual impairments are numerous and complex, in this thesis I focus on addressing the issue of making spatial information of virtual worlds accessible to people with visual impairment through the use of echolocation—sound pulses and their reflection over surfaces to create a mental image of one’s surroundings—Although echolocation is a well-understood phenomenon in the physical world, in this thesis I address the gap in the understanding of the usefulness of echolocation to convey spatial information of virtual worlds.

This thesis comprises three user studies. Study 1 explores the current practices of people with visual impairment who engage with digital games. Through this study, I highlight the significance of digital games to gamers with visual impairments their opinions regarding accessibility of mainstream digital games and explore the elements that facilitate access to digital games. I found that although there is a desire from gamers

## Abstract

with visual impairment to engage with digital games, several factors prevent this from happening, and one of these factors is how games convey spatial information.

Echolocation is a technique that, according to anecdotal accounts in the literature, is used by 20-30 percent of the population of people with visual impairment. Echolocation is used to obtain information about one's physical surroundings. In the first part of study two, which is sub-divided into two parts, I first explore whether it is possible to replicate a sense of echolocation in a virtual world. I found that indeed, it is possible to replicate echo reverberations in a virtual world and that echolocation contributes to establishing a sense of presence in virtual worlds. However, the need to provide proper scaffolding and clear control mechanisms also became evident.

In the second part of Study 2, I explore in more depth the limits of echolocation to acquire spatial knowledge of a virtual world. I found that people with visual impairment can successfully detect different materials a virtual room may be covered in, differences in relative size of virtual rooms, and the presence of 90-degree turns to the left and right approximately 70% of the time. Moreover, I found that openings and obstacles were not easily detectable. Finally, I found that echolocation could be used to assist in the creation of a mental map of a virtual world.

In study four, I follow a participatory design approach to obtain a set of design recommendations to support the implementation of echolocation in virtual worlds. These recommendations highlighted the importance of providing support for passive echolocation, providing support for auditory landmarks, the value of providing precise direction controls, and the importance of using familiar sounds for echolocating. Moreover, the implementation of some of these recommendations resulted in an improved ability to detect openings and obstacles.

Through the three studies presented in this thesis, I provide a comprehensive onlook on echolocation as a new metaphor to support people with visual impairment in the acquisition of spatial knowledge in virtual worlds. The implementation of echolocation and the design recommendations presented in this thesis propose echolocation as a new interaction metaphor with the potential to improve overall accessibility in mainstream games and potentially support the development of orientation and mobility skills of people with visual impairment.



# Declaration

This is to certify that:

- The thesis comprises only my original work towards the PhD except when indicated in the Preface;
- Due acknowledgement has been made in the text to all other material used; and
- The thesis is fewer than 100.000 words in length, exclusive of tables, maps, bibliographies and appendices.

[signed]

Ronny Xavier Andrade Parra





# Preface

## **Work carried out in collaboration with others**

This work is submitted as a Thesis with Publication. As such, the contents of Chapters four, five and six all represent work that has been published previously. Chapter seven is currently under peer-review and chapter eight is written as a publication to be submitted for peer review after the publication presented in chapter seven is accepted.

I was the first author of all the published work included in this Thesis. I was responsible for the research design, data gathering and analysis, and producing a first draft of any published work included in this Thesis. My supervisors were co-authors on each piece of work and Dr. Melissa Rogerson co-authored two of the papers presented in this thesis. The role of my co-authors was mostly advisory, helping me shape the final versions of the published works. I take full responsibility for the accuracy and integrity of the work. Any errors or inaccuracies in the resulting published work are my own.

## **Work submitted towards other qualifications**

No material in this thesis has been submitted for other qualifications, and no work was carried out prior to my enrolment in this degree.

## **Editorial assistance**

No editorial assistance was provided for any section of this Thesis.

## **Contributions in multi-authored publications**

A list of all the publications present in this thesis appear below. Individual reports of contributions in multi-authored publications appear have been submitted separately to the University of Melbourne Thesis Examination System. I have contributed with 70% or more of the work towards each individual publication.

## **Publication status of all chapters presented in article format**

Chapter four: Understanding gamers with visual impairment (*published*)

- Published by the Association of Computing Machinery, in the *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*, May 2019.
- Andrade, R., Rogerson, M., Waycott, J., Baker, S., & Vetere, F. (2019). Playing Blind: Exploring the World of Gamers with Visual Impairment. In *Proceedings of the 2019 CHI Conference on Human Factors in Computer Systems (CHI'19)*, Glasgow, UK.

Chapter five: A framework to understand accessibility in digital games (*published*)

- Published by the Association of Computing Machinery, in the *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*, May 2020.
- Andrade, R., Rogerson, M. J., Waycott, J., Baker, S., & Vetere, F. (2020). Introducing the Gamer Information-Control Framework: Enabling Access to

Digital Games for People with Visual Impairment. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*, Honolulu, HI, USA.

Chapter six: Echolocation in virtual worlds: a feasibility study (*published*)

- Published by the Association of Computing Machinery, in the *Proceedings of the 30<sup>th</sup> Australian Conference on Computer-Human Interaction*, December 2018.
- Andrade, R., Baker, S., Waycott, J., & Vetere, F. (2018). Echo-House: Exploring a Virtual Environment by Using Echolocation. In *the 30th Australian Conference on Human-Computer Interaction (OzCHI'18)*, Melbourne, VIC, Australia.

Chapter seven: Echolocation and spatial information in virtual worlds (accepted for publication)

- To be published by the Association of Computing Machinery in the journal *Transactions on Accessible Computing TACCESS*.

Chapter eight: A participatory design exercise on echolocation

- Unpublished material not submitted for publication.
- To be submitted to the journal *Transactions on Accessible Computing TACCESS*.by the Association of Computing Machinery.

## **Ethics Declaration**

This work was conducted following the University of Melbourne benchmark for Human ethics. Ethics clearance was obtained from the corresponding HEAG and HESC ethics committees before starting each user study. Study 1 received a minimal risk ethics approval (ethics ID 1851274) and studies 2 and 3 received a standard project ethics approval (ethics ID 1749810).

## **Acknowledgement of all sources of funding**

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- My doctoral research was supported by the University of Melbourne through a Melbourne Research Scholarship.
- I received funding for travelling from the Interaction Design Lab and the former Microsoft Research Centre for Social Natural User Interfaces.
- The School of Engineering of the University of Melbourne provided additional travel funding.

This funding allowed me to focus on my doctoral studies, present my research in different venues, attend top conferences in my field, and expand my network of contacts across my field. For those opportunities I am deeply grateful.

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I must recognise the support I received while living and working as a Residential Tutor at International House, the University of Melbourne. I would like to acknowledge the support received by Dr. Deborah Seifert AM, Head of College, who gave me the opportunity to join the IH community. I would also like to thank Mr. Daniel Persaud, Deputy Head, Dr. Katherine Firth, Academic Coordinator, Mrs. Marie McKee, former Academic Coordinator, Dr. Caitlin Stone, IH librarian, and all the rest of the staff, especially the team of residential tutors, for their continuous support. Aidan, Alex, Angela, Brandon, Bresson, Caitlin, Dave, Derrik, Fiona, Eugenie, Georgia, Harry, Jenny and Shaveen. More than a group of co-workers, you have been a real team of friends, and although covid-19 interrupted our hangouts in the SCR, we will have time to celebrate later.

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Finally, I would like to acknowledge the never-ending support received from my parents. Despite being 17,000km and 15-16 hours apart, they have been vigilant of my every step and celebrated each milestone, big or small, with me. This work is dedicated to them.

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| <p>Andrade, R., Baker, S., Waycott, J., &amp; Vetere, F. (2018, 4-7 December 2018). Echo-House: Exploring a Virtual Environment by Using Echolocation. In <i>the 30th Australian Conference on Human-Computer Interaction (OzCHI'18)</i>, Melbourne, VIC, Australia.<br/>© The Authors. Publication rights licensed to ACM. doi: 10.1145/3292147.3292163</p> | p. 146 | N |



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# Section I:

## Foundations



# Chapter 1: Introduction

## 1.1. Context

People with visual impairment rely on assistive technology to engage with computers to complete everyday tasks such as applying for jobs and learning in schools. Screen-reading software, the tool that people with visual impairment most commonly use, converts the contents on a computer screen into spoken text, and through the use of this software people with visual impairment have access to equal opportunities of employment. Furthermore, screen-reading software enables people with visual impairment to participate in the fast-paced communication and knowledge-exchange provided by the Internet (Lazar et al., 2007; Wahidin et al., 2018). As someone who used to work teaching people with visual impairment how to use screen-reading software, I have witnessed first-hand the advantages that being able to engage with technology through screen readers brings to their lives.

However, I also witnessed how, unlike sighted people, engaging with technology for entertainment purposes, such as engaging with digital games, is more difficult for people with visual impairments. I grew up and worked with people with visual impairment in a developing country; this meant that smartphones were not as commonplace and access to computers not as ubiquitous. As a consequence, none of the people I worked with had played any digital games, be it on a gaming console, computer

or mobile device. Even now, about eight years after I stopped working with people with visual impairment in my home country, this remains more or less unchanged. In contrast, most people without visual impairments have become accustomed to consuming digital content, especially digital games, without the need to stop and question whether this content is accessible to all.

Digital games are a particular type of content that is becoming ever-more present in our daily lives. There is an estimate 2.5 billion players worldwide and two in three Australians play digital games in 2019 (Brand et al., 2019). Moreover, the digital gaming industry's net worth has grown from 78.61 billion US dollars in 2017 to an estimated 90 billion US dollars in 2020 (WePC, 2019). For comparison, the movie industry was worth an estimated 75 billion US dollars in 2020 (Witkowski, 2020). However, the reliance of digital games on visual stimuli to convey information renders this entertainment medium inaccessible to people with visual impairment. This is not to say that people with visual impairment do not engage with digital games—as chapter four will demonstrate. People with visual impairment engage with mainstream digital games by either playing as much of a game as they can or by listening to others play mainstream games, otherwise they engage with text-based games or sound-based games—commonly referred to as *audiogames*. This latter type of game has been designed to provide “complete auditory interfaces so that they can be played without the use of graphics” (Friberg & Gärdenfors, 2004). Audiogames provide a source of continuous entertainment for people with visual impairment and have spawned a large community of gamers and developers. I will explain in detail how people with visual impairment engage with digital games in chapters four and five.

Gamers with visual impairment who regularly engage with both text-based adventures and audiogames have expressed their opinions regarding the limitations of audiogames compared to mainstream digital games. While gamers with visual impairment have presented their views about the current state of accessibility in mainstream digital games and praised accessibility initiatives from certain companies such as Microsoft and its Xbox Accessible Controller (Urbanek & Güldenpfennig, 2019), they have also voiced their frustration about the inaccessibility of virtual and augmented reality experiences, which gamers with visual impairment cannot freely explore on their own (Urbanek & Güldenpfennig, 2019). Further opinions of gamers with visual impairment are presented in chapter four.

A key challenge to improving accessibility in digital games for people with visual impairment is the need to clearly convey spatial information (Façanha et al., 2020). This point is emphasised in chapter five. Sighted people rely on their vision to acquire spatial knowledge both in the physical world and in virtual environments (Kitchin & Jacobson, 1997). In contrast, less is known about how people with visual impairment acquire spatial knowledge of virtual spaces. Anecdotal accounts in the literature seem to indicate that the transition from 2D to 3D graphics in digital games in the mid-nineties alienated a number of gamers with low vision by adding more complexity to the spatial layout of digital games (Urbanek & Güldenpfennig, 2019). For example, Urbanek and Güldenpfennig (2019) present the following quote from a gamer with low vision: “*mid ninety’s bang— everything went 3D, and both my spatial abilities with being able to see what’s on the screen and the complexity of the images themselves got to be way too much for my level of sight to cope with*”. The development of 3D games affected the “spatial abilities” of gamers with low vision. This is corroborated later in this thesis.

A proposed solution to this problem presented in several games targeted to people with visual impairment is the use of a grid-like navigation system where the player has a limited range of motion (Ghali et al., 2012). Although this grid-like navigation approach has led to the development of many enjoyable gaming experiences for people with visual impairment, this approach fails to provide an experience that is equitably accessible—that provides comparable levels of agency and efficiency to visually-impaired players—in comparison with mainstream games (Smith & Nayar, 2018). Agency is lost via the reduced range of movement afforded to participants, and efficiency is lost as the “content” of each cell in the grid must be conveyed to the player every time they enter a cell. This loss of agency may be an unintended consequence of this approach to game design. Moreover, the use of such alternative navigation options may be one of the factors preventing audiogames from becoming part of the mainstream gaming culture, as it may lead sighted players to lose interest in audiogames rather quickly (Urbanek & Gldenpfennig, 2019). Additionally, although research proposing the use of grid-like navigation systems has reported improved performance in orientation and mobility tasks in the physical world (Connors et al., 2014), less is known about whether there are alternative ways to render navigation of 3D games—like the ones introduced in the mid-nineties—more accessible.

In physical environments, people with visual impairment use different strategies to freely explore their world. These strategies include the use of a white cane, a guide dog or the use of echolocation. Furthermore, prevalence of the use of different strategies will depend on the degree of the impairment. (Thaler, 2013). Echolocation is the ability to use sound and echo reverberations to build a mental image of their surroundings (Kolarik et al., 2014; Kupers & Ptito, 2014). Although there are no formal statistics on the number



of blind people who can echolocate, anecdotal accounts in the literature claim that 20-30 percent of blind individuals can use echolocation (Wölfflin, 1909; Lamarque, 1929; Villey-Desmeserets, 1930; Thaler, 2013). Its use has been correlated with better orientation and mobility outcomes in unfamiliar places (Thaler, 2013). The physical properties of echolocation are well understood: sharp tongue-clicks are the most effective sound for echolocating (Martínez Rojas et al., 2009), with these clicking sounds having a large spectral content in the range between 6 to 8kHz, and sound levels in the range of 60 to 108dB (Kolarik et al., 2014; Kupers & Ptito, 2014; Schörnich et al., 2012). Moreover, there have been attempts at producing computational models of the tongue-click produced by expert echolocators. Thaler et al. (2017) have captured large samples of clicking sounds produced by expert echolocators and created a computational representation that takes the clicks from experts as inputs and produces an artificial soundwave that simulates these clicks. Furthermore, early research has begun to look at the usefulness of echolocation to explore virtual worlds, albeit with some limitations, which will be explored in more detail in the next chapter (Pelegriñ Garcia et al., 2014; Picinali et al., 2014; Ramos & Arias, 1997; Robinson & Kearney, 2016; Wu et al., 2017).

In this introduction I have provided a broad description of where gamers with visual impairment stand and have pointed at echolocation as a means to better understand spatial information. Before moving on to my framing of the problem to be addressed in this thesis, and to provide the required context for this work, I provide a description of my background and personal experience with disability.

## **1.2. About the author**

In this thesis I am leveraging my own personal experience to inform my approach and understanding of disability. Hence, to fully understand the motivation behind this work, it is necessary to know more about the author, not just about echolocation, games, and acquisition of spatial information. The relevance of my lived experience becomes evident in chapter three, as I articulate the philosophical worldview that underpins this work.

I was born with congenital cataracts on both eyes. To try to correct this, I had two eye surgeries before I was one year of age and have used glasses since. The surgeries were not successful and as a result I lost functionality in the left eye and developed glaucoma on it. Another result of the unsuccessful surgeries was the development of low vision in the right eye. To address the glaucoma in the left eye, I had laser surgery when I was three. The surgery did not return functionality but prevented the development of further complications. Finally, when I turned seventeen, I had an evisceration—removal—of my left non-functioning eye and had a prosthesis put in its place. From the age of three until now I have had no visibility in my left eye and a vision of 20/40, which means I must be 20 feet away to see things that people with “normal” vision can see from 40 feet. All these experiences have made me aware of the medical reality of disability, the importance of diagnosis, and the need for precise measurements when, for example, prescribing glasses.

I am thankful for the medical resources at our disposal, as these enabled me to recover some vision, but not having “normal” vision meant I missed out on some social activities while growing up and relied heavily on family and friends to complete certain tasks. Despite any limitations that may result from low vision, I have always thought of myself as a resourceful person. I pursued an engineering degree and faced some problems

when transitioning to tertiary education, but I learnt to rely on my network of peers to overcome these difficulties. My lived experience with disability taught me the value of the subjective individual experience of reality, while my engineering training fostered in me an appreciation for empirical, practical and replicable solutions.

Finally, while I was completing my undergraduate studies, I was invited to work on a social inclusion program called “*Mis Manos son mis Ojos*” (*My Hands are my Eyes*). This program was developed by the Library and Information Centre of the University where I completed my undergraduate studies, and its aim was to teach people with low vision and blindness technology skills to help them re-join the labour market. I was in charge of teaching students how to use screen-reading software together with productivity software and the Internet. I did this for almost four years. By doing this, I learnt about the realities of others with visual impairments more severe than mine and was glad to contribute to their lives by helping them develop new skills.

To summarise, a congenital condition has given me an appreciation for the need of a medical diagnosis, my training as an engineer has helped me develop a logical approach to problem-solving, while my own limitations while growing up, especially in social aspects, and my working experience with people with visual impairment, has shown me that each person internalises disability differently, and thus each one has a unique subjective experience that is just as valuable. These points will become important when discussing and choosing a worldview to justify the work presented in this thesis.

### **1.3. The problem**

Although people with visual impairment have expressed their desire to engage with digital games and virtual and augmented reality experiences (Urbanek & Güldenpfennig, 2019), these contents remain inaccessible. This is, in part, because it is very challenging to convey spatial information to people with visual impairments. Few audiogames have implemented 3D graphics more as a way to engage with sighted players, and most audiogames use a grid-like navigation system that reduces the ability of the gamer to move freely in the game world. In the physical world, echolocation is a technique used by people with visual impairment to acquire spatial information. Although there is research exploring preliminary implementations of echolocation in virtual worlds (Pelegrin Garcia et al., 2014; Picinali et al., 2014; Ramos & Arias, 1997; Wu et al., 2017), little is known about how echolocation may help people with visual impairment navigate virtual worlds. There is a gap in the way in which spatial information of virtual worlds is being communicated to people with visual impairment and echolocation may provide a useful tool to bridge this gap.

### **1.4. Aim**

The aim of this thesis is to address the gap regarding exploration of virtual worlds by people with visual impairment by investigating the feasibility of using echolocation as a novel interaction technique to acquire spatial information. More broadly, with this work I aim to improve accessibility in digital worlds for people with visual impairment and support the creation of equitably accessible experiences, where the unique skillset and the lived experiences of people with visual impairment are taken into consideration to

produce empowering designs. These aims will be addressed through the implementation of echolocation as an interaction metaphor that may enable people with visual impairment to engage with fully 3D virtual worlds in equality of conditions to sighted players (Rogers & Marsden, 2013; Smith & Nayar, 2018; van de Ven et al., 2005).

There have been previous attempts to implement echolocation in virtual spaces by Ramos and Arias (1997), Pelegrin Garcia et al. (2014), Picinali et al. (2014), Wu et al. (2017) and others. However, these approaches have focused on mimicking echolocation as it occurs in the physical world as accurately as possible, have used pre-recorded echoes, or have relied on a grid-like navigation system for people with visual impairment to explore, thus limiting the directions in which the participants interacting with the proposed technology could move. Moreover, these works have not explored the relation between echolocation in virtual worlds and acquisition of spatial knowledge. In this thesis I implement a 3D virtual world that provides participants with a first-person perspective, similar to what is available in modern mainstream games. Then I propose the use of echoes generated in real time with the aim to better communicate spatial information to people with visual impairment.

### **1.5. Research questions**

The aim stated above can be reformulated as follows:

*How can echolocation be designed as a means for people with visual impairment to acquire spatial knowledge of virtual spaces?*

This research question presents a complex, multi-faceted problem, where technology, lived experience, biological realities and other factors influence the problem.

## Chapter 1: Introduction

Although this thesis contributes to knowledge in the Human-Computer Interaction (HCI) field, it is necessary for me to acknowledge the complexity of exploring the pairing of technology and disability. I will apply a critical realist lens (Shakespeare, 2013) to answer my research question with a pragmatist approach that values both experimental results and the subjective experience of individuals. To better understand the problem, I have divided my research question into five sub-research questions (RQs):

- **RQ1:** How do people with visual impairment currently engage with virtual spaces (digital games and augmented/virtual reality experiences)?
- **RQ2:** How can echolocation be implemented in virtual worlds so that it supports acquisition of spatial knowledge?
- **RQ3:** What features of virtual space can be revealed through echolocation?
- **RQ4:** How do the features revealed through echolocation support acquisition of spatial knowledge in virtual space?
- **RQ5:** How can a co-creation process inform the design and implementation of echolocation in virtual spaces?

RQ1 focuses on the personal experience of people with visual impairment and digital games. Moreover, further reflection on the findings from RQ1—to be described in chapter five—helped shape the main research question of this work, shown above. This process where feedback from participants is incorporated in this work as it progresses is an important aspect of this thesis. RQ2, RQ3 and RQ4 provide an experimental solution to the problem posed by the overall research question, and RQ5 brings the focus back to the lived experience and the expertise of people with visual impairment. These research questions are addressed through a series of user studies described in the subsequent chapters of this work.

## 1.6. Scope

For the purposes of the studies performed as part of this thesis, I will follow the definition of blindness and low vision provided by Vision Australia: a participant will be considered blind if “they cannot see at six metres what someone with normal vision can see at 60 metres or if their field of vision is less than 20 degrees in diameter” (*Blindness and Vision Loss*, n.d.). A participant will be considered to have low vision if “they have permanent vision loss that cannot be corrected with glasses and affects their daily functioning” (*Blindness and Vision Loss*, n.d.). These definitions are inclusive of people who are totally blind. However, relying on these definitions likely excludes a large population with less severe visual impairments who may also benefit from this research.

Ageing is correlated with a degeneration of vision, particularly in the form of presbyopia—long sightedness caused by loss of elasticity of the lens of the eye, occurring typically in middle and old age. This condition has a prevalence of 40.3% among people aged 50 years or older (Bourne et al., 2017). However, in all the studies that comprise this thesis I purposefully avoided recruiting participants who have acquired low vision or blindness as a consequence of ageing. This was done to recognise the unique skills that people with a lived experience of vision impairment would bring into the user studies.

Similarly, a decision was made not to include blindfolded sighted individuals, as this approach tends to replicate the shock of losing sight without replicating the skills that a person with visual impairment must learn in order to navigate the world (Silverman, 2015). Additional to these practical considerations, chapter three describes the philosophical arguments under which it is not acceptable to recruit sighted blindfolded individuals as suitable participants.

## Chapter 1: Introduction

In this work, a virtual world is the space where a digital game takes place and it may or may not involve game elements such as lives and points systems (Bergonse, 2017). The user studies conducted in this thesis are performed in virtual worlds, even though I may draw parallels with digital games or may use the terms interchangeably. This is because digital games are the most well-known examples of virtual worlds. Furthermore, as no game elements have been included in the worlds designed for each user study, these do not qualify as fully-fledged digital games. More detail on the distinction between virtual world and digital game is provided in chapter two.

Finally, familiarity with virtual worlds or gaming literacy was not required for participation in the user studies described in this thesis. This decision was made reflecting on my own personal experience working with people with visual impairments, as none of the people I worked with had had any gaming experience prior to or after losing their sight.

### **1.7. Thesis overview**

The content of this thesis is structured as follows: Chapter two provides an overview of previous work describing how people with visual impairment acquire spatial information, the approaches taken to make digital games accessible and convey spatial information in virtual worlds, and a detailed literature review on echolocation, with existing implementations in virtual worlds. Chapter three presents the reader with the worldview I have chosen to inform my conceptualisation of the world and knowledge in it, discusses the different lenses that have emerged to describe disability, outlines the methodology that informed this work, and defines the methods to be used in subsequent user studies to explore the different research questions. Together, chapters one, two and three comprise



the first section of this thesis, called Foundations, and provide a theoretical foundation to this work.

The second section of this thesis is called People and comprises chapters four and five. Chapter four aims to provide an understanding of the real-world experience of gamers with visual impairment, focusing on their habits, opinions and concerns, and chapter five focuses on describing the elements that expert gamers with visual impairment have found critical in the development of accessible games. Moreover, one of the key findings outlined in chapter five is the notion that conveying spatial information is key to improve accessibility in digital worlds.

Chapters six through nine comprise section three, entitled Echolocation Implementation. Chapters six through eight present user studies where echolocation is implemented as a mechanism to explore virtual worlds and chapter nine provides an integrated discussion of the findings of this thesis. Chapter six describes a feasibility study to determine whether it was possible to implement echolocation in virtual worlds at all. Chapter seven describes a user study that builds upon the findings from the previous chapter and proposes an in-depth analysis of the use of echolocation to acquire spatial knowledge of virtual spaces. Chapter eight describes a final user study, which focused on using a participatory design approach to refine the current implementation of echolocation in virtual worlds by learning from a group of expert echolocators and incorporating their views into the design of echolocation-enabled virtual worlds. Finally, Chapter nine presents a discussion of the implications of this work, a summary of the limitations, future directions and conclusions of this work.

## 1.8. Summary of key findings

The aim of this section is to provide a brief overview of the main findings derived from this work. More details on how these findings were obtained are presented throughout this thesis, particularly in chapter 9.

**RQ1:** *how do people with visual impairment currently engage with digital games?*

This work finds that although many people with visual impairment wish to engage with digital games in the same capacity as their sighted counterparts, there is a tension between designing games that are accessible and fun. Moreover, this work also describes the importance of the relationships with information—particularly spatial information—and elements of control as key enablers to the development of games that are accessible to people with visual impairment. More details on these findings are presented in chapters 4 and 5.

**RQ2:** *How can echolocation be implemented in virtual worlds so that it supports the acquisition of spatial knowledge?* This thesis posits that it is possible to create such an implementation of echolocation. However, this thesis acknowledges the need to help people with visual impairment develop the proper skillset to use echolocation through scaffolding. For more details, refer to chapter 6.

**RQ3:** *What features of virtual space can be revealed through echolocation?*

Experiments presented in chapter 7 demonstrate that it is possible for people with visual impairment to identify: (i) the material that a virtual room is made of, (ii) the relative size across three different virtual rooms, and (iii) the presence of 90-degree turns to the left or right approximately 70% of the time.

**RQ4:** *How do the features revealed through echolocation support the acquisition of spatial knowledge in virtual space?* Experiments presented in chapter 7 led to the conclusion that people with visual impairment are able to successfully integrate discrete spatial features into a holistic mental image of virtual space. Moreover, findings from chapters 7 and 8 support the notion that echolocation aids in the development of a sense of being present in the virtual space.

**RQ5:** *How can a co-creation process inform the design and implementation of echolocation in virtual spaces?* Upon conducting a participatory design exercise with expert echolocators—described in chapter 8—this work presents a series of design recommendations informed by the lived experiences of expert echolocators. By devising these recommendations together with participants, this work aims to ensure their voices are heard and inform future design.

## **1.9. Summary**

In this chapter, I have presented the problem to be addressed in this thesis: the lack of mechanisms to convey spatial information to people with visual impairment in virtual worlds. I have provided a context to this problem as well as background information about myself and how my lived experience informs this work. In this chapter I have also suggested the use of echolocation as a novel interaction technique to acquire spatial information in virtual worlds. I have outlined a series of research questions to be explored, described the scope of this work, and provided an overview of the contents of the overall thesis. In the following chapter I describe the work that has been done by previous researchers in the areas of acquisition of spatial information, echolocation, and accessibility in digital games.



# Chapter 2: Previous Work

## 2.1. Introduction

Chapter one described how digital games are inaccessible to people with visual impairment, noting that because these games rely on visual stimuli to convey spatial information, it can be difficult for people with visual impairment to acquire knowledge of the 3D space within virtual worlds. Chapter one also identified echolocation as a navigation tool that people with visual impairment use to negotiate their surroundings in the physical world. Moreover, chapter one presented the research questions to be investigated in this thesis and limits the scope of this work.

This chapter delves more deeply into these topics and provides a comprehensive survey of current knowledge concerning accessibility in digital games. This discussion centres around three key topics: *games and accessibility* (sections 2.2 and 2.3), *echolocation* and its usefulness in learning about one's surroundings (section 2.4), and *spatial information* acquisition and evaluation (section 2.5). The discussion about accessibility in games explores physical games as a starting point, then moves on to describe the current state of accessibility in the digital games industry, and how people with visual impairment currently engage with digital games, particularly in the form of text-based adventures and audiogames. The revision of existing literature on echolocation focuses on what echolocation is, how it functions, what information can be learnt through

## Chapter 2: Previous Work

its use, how previous researchers have attempted to implement it in virtual worlds, and the results they have obtained. Finally, the revision of existing literature on acquisition of spatial knowledge focuses on three key concepts: *landmarks* (2.5.1), *routes* (2.5.2) and *mental maps* (2.5.3), with particular emphasis on how mental map formation is evaluated. As I examine these three topics in this chapter, I will argue that:

- Accessibility in both physical and digital games is a growing field of research and practice, where industry incumbents have started to play a significant role.
- Although most digital games rely heavily on visual stimuli to convey information, people with visual impairment have found workarounds to circumvent obstacles and engage with digital games, particularly through text-based adventures and audiogames.
- Echolocation is a well-understood phenomenon, to the point that there have been preliminary attempts to implement echolocation in virtual worlds. However, these attempts have not explored how echolocation may relate to the acquisition of spatial information in virtual worlds.
- There is a clear understanding of how people with visual impairment acquire spatial information in the physical world, and the role of landmarks, routes and mental maps in spatial information acquisition is well differentiated. However, little is known about how the ability to acquire spatial information translates to virtual worlds.

The analysis of previous work described in this chapter highlights the novelty of the work presented in this thesis and identifies existing gaps that justify the necessity and importance of the research I have undertaken. Moreover, the diverse literature consulted

for this chapter—ranging from research in the fields of social studies, neurobiology, sound engineering, human-computer interaction, and others—demonstrate the interdisciplinary nature of this research and highlights that this research draws from, and contributes to, multiple areas of related work.

## **2.2. Physical games and accessibility**

Before focusing on digital games, this section describes existing literature on accessibility for people with visual impairment in physical games, as some of the lessons that have been learnt about games in the physical world apply to digital games. Games have accompanied humanity for millennia, with evidence of the existence of games—specifically boardgames—as early as the seventh millennium BCE. in the Near East, where some of the very first large human settlements were located (Sebbane, 2001). This close historic connection between humans and games may be because play is a fundamental desire that is rooted in human nature (Sebbane, 2001).

One of the key reasons why games have remained relevant through time is their materiality (Rogerson et al., 2016). This concept is not limited to the physical nature of the elements of a game, but also encompasses the affordances provided by these elements (Gross et al., 2014). However, the physical aspect of materiality has been the main focus of accessibility efforts in recent game studies (Heron et al., 2018a). Regarding accessibility in physical games, Heron et al. (2018a) stated that “it’s important that players know what parts of the game are relevant to them, which parts are relevant to other players, and what that relevance means for their own future actions and activities” (p. 85). To communicate this knowledge to people with visual impairment, emphasis has been placed on the physical elements of games.

Heron et al. (2018a) and Heron et al. (2018b) provide an excellent overview of accessibility in physical games for people with different types of impairments. Heron et al. (2018a) have looked at a list of 116 board games and have identified an extensive list of common accessibility issues that arise from the physical nature of the components of the games. Heron et al. (2018a) have developed a series of accessibility categories for games and a numerical accessibility score. This score indicated how strongly the authors recommended a game, depending on the accessibility category being assessed. According to their scoring system, the average accessibility of all 116 boardgames evaluated was 7.04 out of 14 in the category of accessibility for *people with visual impairment*. This average corresponds to a score between “tentatively recommended” and “not recommended”. This means that, on average, it is hard to find a boardgame that is accessible enough to be recommended to people with visual impairment. Moreover, the authors indicate that this score was artificially skewed upwards due to the fact that many adaptations that work for people with low vision do not work for people who are blind.

Heron et al. (2018b) propose the following strategies to improve accessibility in physical games for people with visual impairment: choosing a colour palette that is accessible to people who are colour blind; ensuring effective colour contrast of the game elements; choosing fonts that prioritise readability over ornamentation; using font size of 14 or higher; providing tokens that can be differentiated by touch; and being mindful of elements that are usually inaccessible such as paper money or dice. These recommendations are indeed useful to improve accessibility in games for people with visual impairment. However, they are rooted in the physical nature of these games. Although some of these recommendations may not be hard to translate into digital games, it is clear that—just like with physical games—they are likely to benefit people with low



vision over blind people. As Rogerson et al. (2016) indicates, affordances are an important part of the appeal of games, and they may provide an opportunity to tackle accessibility in digital games beyond focusing on their physical nature.

In the second half of the twentieth century the development of computers enabled the development of digital games, a new type of game that takes place “in a digital environment... and [involves] no physical interaction with the game itself” (Rogerson et al., 2016, p. 3956). Digital games were initially developed and played by hobbyists. Engaging with these games was a niche activity, as access to computers was limited and technical knowledge was required (Heron, 2012). However, nowadays digital games have become a ubiquitous cultural phenomenon and an industry worth billions of dollars (Brand et al., 2019; WePC, 2019). As these games rely heavily on visual stimuli to convey information, people without a “normal” level of sight struggle to engage with these games (Clarkson et al., 2015). By being unable to engage with digital games, people with visual impairment are excluded from participating in the broader cultural discourse and from establishing social connections through shared activities.

### **2.3. Digital games and accessibility**

This section explores how people with visual impairment engage with digital games and the approaches the mainstream gaming industry has taken to improve accessibility in their games. The discussion focuses on specialised games for people with visual impairment: text-based games and audiogames.

## Chapter 2: Previous Work

### 2.3.1. Virtual world or videogame?

Before moving forward with the discussion about accessibility in digital games, it is necessary to clarify some of the vocabulary to be used. It is particularly important to understand the difference between terms such as virtual world, videogame or digital game. Kruger and van Zijl (2014) define virtual worlds as constructs where “software is used to simulate reality by defining objects, and rules on how these objects should behave and react” (p. 1). Moreover, Kruger and van Zijl (2014) explain that virtual worlds are used in different contexts, including gaming, education and communication. This definition of virtual world presents them as a foundation that determines basic interactions between the simulated world and the elements that reside in it.

Bergonse (2017) builds on the idea of virtual worlds presented by Kruger and van Zijl. According to Bergonse (2017), a videogame is defined as a mode of interaction that occurs in an environment, is subject to the rules of said environment, and involves one (or more) players. Bergonse acknowledges the need for the environment to precede the game and agrees that the elements of the game must be subject to the rules of the environment. In other words, a videogame occurs within a virtual environment. Additionally, Bergonse (2017) argues that a videogame may or may not involve gameplay. The difference between videogame and digital game is more difficult to pinpoint, but for the purposes of this thesis, the terms may be used interchangeably. Finally, *audiogames*—explored in more detail later in section 2.3.6—are a subset of digital games that rely on auditory feedback to convey information about the state of the game and its world (Friberg & Gärdenfors, 2004). Figure 1. Relationship between virtual worlds, videogames and audiogames shows the relationship between virtual world, videogame and audiogame.

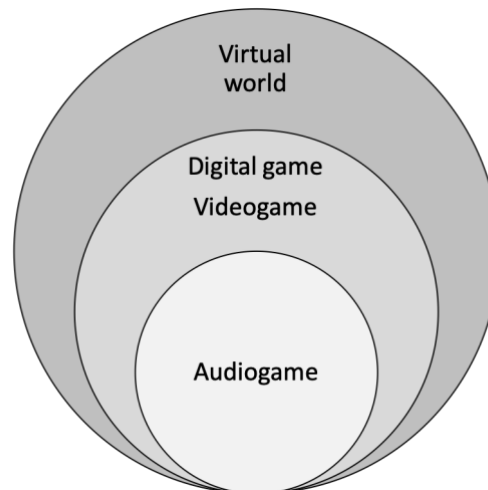


Figure 1. Relationship between virtual worlds, videogames and audiogames

In this thesis, I will favour the term “virtual world”, as the virtual world precedes the gaming experience and I believe that it is best to address accessibility at a broader level. Additionally, the technology solutions that are described in section three of this thesis do not include any discernible gaming element such as enemies, story or obstacles and can be easily applied to different settings such as desktop computers or virtual reality headsets, so they can be categorised as virtual worlds. However, the related work presented in this chapter centres around digital games because these are the instances of virtual worlds with which we are more familiar.

### 2.3.2. How people with visual impairment engage with digital games

Some people with visual impairment are interested in engaging with digital games. Anecdotal pieces appear from time to time on mainstream media about blind gamers playing *Nintendo Switch* games (Cloutier, 2017), accumulating more than 7,500 deaths in the game *Call of Duty, WWII* (Lumb, 2018) or acing online matches against sighted players in fighting games such as *Mortal Kombat* (Welch, 2019). Despite this interest,

not much can be found in academic literature about how people with visual impairment engage with mainstream games. Instead, academic literature that explores how people with visual impairment engage with digital games is usually limited to the introduction of a custom-made gaming experience and its evaluation.

Porter and Kientz (2013) highlight the disconnect between academic literature, the mainstream gaming industry, and the experiences of gamers with visual impairment. In an empirical study consisting of an online survey with 55 gamers with different disabilities and in-depth interviews with six people involved in different roles in the game development industry, the interviews revealed that:

- Game developers prioritise implementing “low hanging fruit” features, such as colour-blindness accessibility or adding captions to cut scenes.
- Accessibility needs a champion—accessibility features are implemented in games when someone at a company is affected by a disability.
- There is pressure to adhere to external accessibility standards.
- Many of the sub-systems used for game-development make it hard to implement accessibility features
- It is particularly challenging to implement accessibility features in console games due to limitations in input hardware and the “closed-wall garden” nature of such consoles.

Findings from Porter and Kientz (2013) describe the state of accessibility in the gaming industry from the point of view of game developers. Most of the findings made by Porter and Kientz (2013) hold true to this day (Aguado-Delgado et al., 2020) This description highlights issues regarding the attitudes of developers and the limitations of existing development tools. In the case of developers, for example, they suggested the

need for an accessibility champion, instead of incorporating accessibility thinking as a default. In the case of development tools, the closed wall nature of game consoles may discourage developers from creating accessibility features in the first place.

As digital games have become part of mainstream culture, it is important to ensure that everyone can access them regardless of physical ability. The charity AbleGamers is an example of an organisation committed to this goal. According to their website<sup>1</sup>, “AbleGamers gives grants of assistive technologies to people with disabilities in need of financial aid enabling them to play video games just like anyone else”. Although providing financial support to that people with disabilities can engage with digital games is a remarkable action, it is necessary to ensure that games accessible by default. To work on this front, AbleGamers also supports research by pairing researchers with people with disabilities who have expressed interest in participating in research projects.

Beeston et al. (2018) conducted a demographic survey with 230 gamers with disability with the support of AbleGamers. Approximately 24% of Beeston et al. (2018) participants self-identified as being blind, colour vision deficient or having low vision. Based on their findings, Beeston et al. (2018) argue that the gaming preferences of people with disabilities are no different from that of non-disabled digital game players. Their findings also suggest that people with disabilities enjoy playing multi-player games. Although the results from Beeston et al. (2018) are not categorised by disability, they are a good reference point to understand the profile of gamers with visual impairment. Moreover, these results coincide with the findings from the study I will present in chapter

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<sup>1</sup> <https://ablegamers.org/>

four, where I explore the habits, opinions and concerns of a group of gamers with visual impairment.

Finally, there is an economic argument to be made in favour of including accessibility measures in digital games: it is easy to assume that the sector of the population that may benefit from accessibility enhancements in games is small when compared to the overall population who engage with digital games. However, in the United States alone there are 33 million gamers with a disability (Moreno, 2017), and recent research conducted in Australia has uncovered that designing for everyone may increase the number of intended customers by a factor of four (Brand et al., 2019). As Porter (2014) argues, the attention that accessibility in mainstream games has received in recent years “lacks adequate consideration of the real-world context of the mainstream gaming”. It is time for mainstream game development companies to look at accessibility as an opportunity to reach a larger sector of the market instead of as a task that is limited to grabbing the “low hanging fruit” and depends on accessibility champions instead of on industry standards. It is the aim of this thesis to demonstrate that new modalities of interacting with digital games, such as echolocation, enable mainstream game developing companies to improve the accessibility of their games, thus enabling to grow their market share by making games more accessible to all.

### 2.3.3. Accessibility trends in the gaming industry

Porter and Kientz (2013) have broadly described the opinions of people involved in the game development industry regarding accessibility in digital games and Aguado-Delgado et al. (2020) indicate that although more research has been conducted in this space, not much has changed. These opinions have been translated into concrete actions taken by

the game development industry, such as using colour palettes that are accessible for colour-blind people or including subtitles in cutscenes (Porter & Kientz, 2013). These actions coincide with some of the recommendations made by Heron et al. (2018a) regarding accessibility of physical games and aim to make games more accessible. However, Mut (2019) argues that, in practice, the responsibility for improving accessibility in games has fallen on the gamers themselves, who have had to create custom hardware to engage with digital games. Mut (2019) recognises that this has started to change over the last four or five years, and cites the following examples as demonstrations of changes in the industry: Microsoft's Xbox Adaptive Controller, a device with large programmable buttons aimed at people with limited mobility; the Tobii eye-tracking peripheral, which allows players to move the game camera with their eyes; implementations of text-to-speech interfaces—especially in the Xbox console; the ability to remap buttons in games and at system-level, and text augmentation features in the Sony PS4. Porter and Kientz (2013) and Mut (2019) agree that accessibility should be the default consideration taken by the mainstream gaming hardware and software producers. Accessibility needs to be addressed by the industry as a whole in order to deliver experiences that are equitably accessible to all, regardless of physical ability (Smith & Nayar, 2018), and the role of research is to provide knowledge to guide the development of these experiences. This is especially relevant when exploring new and emerging technologies, such as virtual and augmented reality (VR/AR) experiences.

Despite the progress being made in the gaming industry towards the development of more accessible games, specialised games outlets such as Polygon have noted that there has been a recent pushback *against* accessible games by a small but loud part of the gaming community (Parlock, 2019). This pushback comes from the inclusion of “easy”

modes in recent videogames. The use of these modes is perceived as either cheating or going against the original artistic vision of the game designers (Fahey, 2019; Parlock, 2019). However, this argument lacks substantive weight: the inclusion of an easy mode does not force players to use it, easy modes are just one of many tools available to improve accessibility in games, and most importantly, the goal of including easy modes is to *deliver equality of outcome*. That is, enabling anyone to engage with a game regardless of ability (Fahey, 2019; Powers et al., 2015).

### 2.3.4. Accessibility in virtual and augmented reality (VR/AR)

#### **Virtual reality**

Virtual reality refers to the perception of elements “in an environment other than that in which [the user] physically exists” (Ellis, 1995, p. 324). Although this is a broad definition, Ellis (1995) clarifies that the most advanced virtual environments—what we now associate with VR experiences—include a series of visual tricks such as first-person motion parallax, depth-of-focus variation and a wide field of view. These optical tricks are usually achieved by using head-mounted displays and if they are convincing enough, they can deliver the illusion of telepresence—of being part of the simulated environment (Ellis, 1995). Additionally, these virtual reality experiences may involve high-fidelity sound and haptics. However, the computational power required to create real-time convincing auditory output is high, and haptics are usually possible within very specific applications (Sanchez-Vives & Slater, 2005). Despite the complications associated with high-fidelity sound and haptic feedback, these have been the main techniques utilised when trying to make these inherently visual virtual experiences accessible.



Examples of virtual reality experiences that rely on auditory feedback to improve VR accessibility are presented by Gonzalez-Mora et al. (2006) and Tiponut et al. (2008), who have created a VR experience where the objects in the virtual environment emit sounds to alert users of their presence. Another example is provided by Seki and Sato (2011), who used binaural audio and individual listening profiles via the use of head-related transfer functions (to be explored in more detail in section 2.4) to simulate cars passing by and in so doing train participants in orientation and mobility. Regarding the use of haptic feedback, this is used to simulate the experience of using a white cane and is usually delivered through desktop-mounted force feedback devices that simulate the tactile sensation provided by a white cane (Lecuyer et al., 2003). Although these desktop-mounted systems provide feedback regarding the presence of objects and their texture, they require the user to remain stationary. A more complex cane-like device that can be used to explore VR experiences is presented by Zhao et al. (2018), who provide the users with a brake mechanism that prevents physical movement of a physical cane when it collides with objects in a virtual world, vibrotactile feedback to simulate the cane hitting virtual objects or being dragged, and sounds simulating real-world cane interactions.

The approach of adding sounds and objects to existing systems has limitations: objects that emit sounds may seem unrealistic to participants and break the effect of immersion (Gonzalez-Mora et al., 2006; Tiponut et al., 2008); creating individual listening profiles is computationally expensive and requires dedicated equipment (Seki & Sato, 2011); the use of haptic feedback requires the use of hardware that may not be available outside the laboratory (Lecuyer et al., 2003; Zhao et al., 2018).

### **Augmented reality**

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Augmented reality (AR) is defined as “a real-time direct or indirect view of a physical real-world environment that has been enhanced / *augmented* by adding virtual computer-generated information to it” (Carmigniani et al., 2011, p. 342). As augmented reality overlays the physical world with digital images or text, making AR accessible for those with reduced vision is a challenge, especially for people who are blind.

Researchers have looked at the use of augmented reality glasses as accessibility devices by studying the ability of people with low vision to identify objects or read text in commercial AR glasses. These experiments have revealed that people with low vision can identify large shapes and read short phrases with large and thick fonts using AR glasses (Zhao et al., 2017). AR glasses have been used to compensate for colour blindness (Langlotz et al., 2018) and to provide assistance in reading signs to people with low vision (Huang et al., 2019). Despite the potential applications of AR glasses as assistive tools, research on how to design accessible AR *interfaces* remains largely unexplored. This is reflected in the inaccessibility of mainstream AR experiences. Chapter four provides a reflection on the inaccessibility of mainstream AR applications—specifically of the popular game *Pokémon Go*, which reached 800 million downloads, amassed almost \$2 billion in revenue in 2018 and brought AR to the attention of mainstream audiences. (Chamary, 2018).

Analysis of gaming trends suggests that AR and VR are about to increase in popularity. According to the report on gaming trends by ESA (2017), one in three “of the most frequent gamers said they were ‘likely to buy VR in the next year’” (p. 9). As current trends seem to suggest that VR and AR currently sit at a point of near-maturity and mass market adoption (ESA, 2017; Mott et al., 2019), it is critical to ensure that these technologies consider accessibility as an integral part of their design (Mott et al., 2019).

Furthermore, I will demonstrate in chapter four that people with visual impairment desire to engage with these technologies but are prevented by their lack of accessibility. Finally, VR/AR experiences, just like digital-game experiences, occur within virtual worlds (Figure 1), so the findings of this work will also be relevant for AR/VR.

Apart from initiatives from mainstream game development companies and the later developments in VR and AR described above, there have been other initiatives that have resulted in games specifically targeted to people with visual impairment. Text-based games and audiogames are games that provide an accessible interface and aim to deliver an enjoyable experience to gamers with visual impairments. The following sections describe these types of games.

#### 2.3.5. Text-based adventures

Adams and Rollings (2006) define text-based adventures as a type of adventure game where the entire interface *can be* text only, with static images or sounds being optional elements, and where the interaction with the game world is driven by typing text commands. These games first appeared in the mid 1970s (Bartle, 2010). Some of the first titles in this genre, and some of the first videogames ever created for that matter, include *Colossal Cave Adventure*, *Zorg* and *MUD1*. *MUD1* stands for Multi-User Dungeon. The *MUD1* text-based adventure was developed by Roy Trubshaw and Richard Bartle, and started a new type of text-based adventure where several players could simultaneously interact in the game world, thus becoming a true predecessor of MMOs (Massively Multi-player Online) (Bartle, 1996, 2010).

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Despite the text-based nature of MUDs, Bartle (1996) argued that a large number of MUD players engaged with these games due to their interactive nature and the players' desire to explore the virtual world. This suggests that graphics are not necessary to engage with digital games for exploration purposes. Moreover, the fact that the content in these games is delivered through text makes them accessible to screen readers, a type of assistive technology that converts computer text input into auditory output (Wahidin et al., 2018). Despite these advantages, MUDs also have limitations: they force players to learn a set of commands to interact; in several cases these commands need to be typed verbatim and without the possibility to replace keywords with synonyms. More importantly, as computer graphics and the Internet have become more widespread since the mid 90s, MUDs failed to become as popular as other gaming experiences. Particularly, MUDs were “replaced” by Massively Online Multiplayer Role-Playing Games (MMORPGs), such as *Second Life* and *World of Warcraft* (Bartle, 2010). Chapters four and five re-visit the fact that, to this day, people with visual impairment continue to engage with MUDs, despite them being based upon pieces of technology that appeared decades ago. This demonstrates the accessibility challenges that continue to impact on gamers with visual impairment.

### 2.3.6. Audiogames

Audiogames are an alternative for people with visual impairment to engage with digital games. These games aim to deliver auditory experiences that are as close as possible to mainstream games and can be played without the need for graphics (Atkinson et al., 2006; Friberg & Gärdenfors, 2004). To deliver an entirely auditory experience, audiogames must rely on voice, earcons and auditory icons. Voice has been used for driving the

narrative of the game and to provide feedback rather than as an interaction mechanism. Interestingly, even though voice has been identified to be easier to process than other auditory alternatives (Sanchez-Vives & Slater, 2005), voice interfaces are seldom used in mainstream games (Allison et al., 2017) or in games for people with visual impairment (Sánchez et al., 2015).

Gaver (1986) and Blattner et al. (1989), who conducted seminal research on the use of earcons and auditory icons in computer interfaces, explained that earcons are artificial tones that are used to convey actions—such as the ringing sound of a phone, or in the case of a game, a sound that indicates game progress has been saved; while auditory icons are sounds that emulate sounds from the physical world to indicate an action—such as the sound of crumpling paper when emptying the Trash Bin on a computer, or in the context of a game, the use of various environmental sounds such as the chirpings of birds.

Problems with sound-based games include the non-persistent nature of sound and the limited approaches to support exploration in audiogames. By nature, sounds are lineal and fleeting. Hence, the information that is available to players at any given time is constrained by the temporality of sound and players need to have sounds repeated to them if they want to access information that has already been conveyed (Kirke, 2018). This is in opposition to visual scenes, where players can gain information about the state of the game world at a glance.

Regarding exploration options available in audiogames, a common approach described by Ghali et al. (2012) is the use of a grid-like system that allows players to move in pre-determined directions. Popular audiogames such as *Castaways* and *Swamp* (Kaldobsky, n.d.) use this approach to exploration. This provides a simplified approach to navigation that is not on par with what is available in modern games, where players

can explore fully tridimensional environment from a first- or third-person perspective. Smith and Nayar (2018) have criticised this limited approach to audiogames and have argued for games that are “equitably accessible”, where even if interaction patterns are different, players with visual impairment receive the same level of agency and efficiency as sighted players who engage with mainstream games. Moreover, Smith and Nayar (2018) identified complexity as a critical element to delivering an engaging gaming experience for people with visual impairment. This is later corroborated in research presented by Urbanek and Güldenpfennig (2019) and in chapter four of this thesis, where expert gamers with visual impairment support the idea that complexity is a key factor for the development of engaging audiogames.

### **Examples of audiogames**

One of the first appearances of audiogames in scholarly literature is in the work of Sánchez and Lumbreras (1999), who developed *AudioDoom*, an audiogame for children who are blind where they explored a virtual environment through the use of binaural sounds and were asked to reproduce the in-game environment with modelling materials after finishing interacting with *AudioDoom*. Similar to Sánchez and Lumbreras (1999), there have been several other academic articles where researchers introduce an audiogame and evaluate it with a group of people with visual impairment. For example, Lahav et al. (2012) proposed the use of haptic feedback to help people with visual impairment to build a mental image of virtual spaces and used a completion task, where participants were given blocks to replicate the virtual environment. Other researchers who developed an audiogame to assist with development of orientation and mobility skills are Connors et al. (2014), who developed the *AbES* (Audio-based Environment Simulator),

a tool that uses a grid-like navigation system to model virtual environments based on real-world locations. Connors et al. (2014) found a positive correlation between success in using the *AbES* and satisfactory navigation of unfamiliar environments.

Audiogames have been used to teach people with visual impairment to learn Braille. *BVGhost*, developed by Milne et al. (2013), is a smartphone game that uses audio and haptic feedback to reinforce Braille concepts. Expanding on their own work, Milne et al. (2014) present a collection of mobile games to encourage Braille literacy in a fun way. Another popular example of an audiogame developed for educational purposes is *PowerUp*, by Trewin et al. (2008). This is an educational virtual environment that included a series of features that made it accessible to children with a diverse range of disabilities, including low and no vision.

The literature also shows examples of audiogames developed for the sake of developing an enjoyable experience for people with visual impairments. Such examples include *Terraformers*, developed by Westin (2004). This 3D game provides a series of accessibility features, including a sound compass, a sonar, a high-contrast mode and the possibility to turn off the graphics completely. Another audiogame developed purely for entertainment purposes is *AudioQuake*, by Atkinson et al. (2006). It proposes a series of accessibility adaptations to the classic first-person shooter *Quake* in order to make it accessible to people with visual impairment by using binaural sounds and a carefully crafted collection of earcons and auditory icons. Finally, a third example of an audiogame designed for hedonic purposes is *Blind Hero*, by Yuan and Folmer (2008). This game was inspired by the popular *Guitar Hero*, a game where players used a fake guitar to simulate that they play along popular songs. In *Blind Hero*, participants used a glove that provided

haptic feedback as a replacement of the visual feedback provided by the original *Guitar Hero*.

The list of audiogames presented so far is by no means extensive and is only used to illustrate different goals considered when designing and evaluating audiogames in academic literature. For detailed literature reviews on the evolution of audiogames over time, refer to Westin et al. (2011), who summarised 20 papers (published between 2005 and 2010) that studied the implementation and evaluation of games that were accessible to people with visual impairment. Yuan et al. (2011), who listed the most popular games for people with visual impairment found on the website **www.audiogames.net** in 2010 and identified common accessibility strategies available in these games. Mangiron and Zhang (2016), who identified that gamers with visual impairment either play mainstream games assisted by sighted players, play adapted versions of mainstream games, or play games specifically designed for people with visual impairment. Kirke (2018), who provides a historical review of the development of audiogames both in mainstream consoles, and as niche games that target people with visual impairment specifically. Finally, the most recent and ambitious review on audiogames in academic literature is presented by Urbanek and Güldenpfennig (2019), who conducted a systematic search of the literature in top research databases to identify articles related to audiogames published over the last twenty years. Upon manual curation, Urbanek and Güldenpfennig (2019) identified 128 relevant papers, and through the use of grounded theory methods, identified four constructs that support accessibility across these games: ways of crafting the user experience, a focus on user experience and evaluation, a link between technological progress and audiogames, and different input and output technologies used in audiogames.



Audiogames have also appeared outside academic publications. The website **www.audiogames.net** provides a large database of over 500 audiogames that includes commercial software, free software (freeware) and software whose development has ceased (abandonware). This site also hosts a large community of gamers with visual impairment that engage with audiogames as both players and creators, and actively participate in discussions about their games through forum posts. Furthermore, Urbanek and Güldenpfennig (2019) describe the community found in audiogames.net as a Community of Practice, as per the definition provided by Wenger (1999), where the members of the community share a domain of interest, build strong relationships that allow them to learn from each other, and are practitioners with a wide array of resources. Future chapters of this thesis leverage this community of practice to provide a better understanding of the characteristics of gamers with visual impairment.

In summary, implementations of audiogames have been developed with a set of various goals in mind: from helping people with visual impairment to developing orientation and mobility skills (Sánchez & Lumbreras, 1999) to learning Braille (Milne et al., 2013) to just having fun (Yuan & Folmer, 2008). Moreover, the existence of a community of practice around audiogames demonstrates their importance. However, little is known about what types of audiogames members of the audiogaming community currently engage with and what makes audiogames enjoyable from the point of view of gamers with visual impairments. These questions will be addressed in chapters four and five.

### **Design patterns in audiogames**

Some authors have proposed patterns to guide the design of audiogames. Trewin et al. (2008) recommended the following to make the graphical user interface (GUI) of a digital

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game more accessible: allowing for text customisation in elements of the GUI, such as menus; providing keyboard navigation for all the elements of the GUI; providing point-and-click control, this is, ensuring all elements of the GUI respond to the cursor, and providing an on-screen keyboard when necessary; providing self-voicing capabilities to the elements of the GUI; and providing sounds and captions when needed.

When making 3D worlds accessible, Trewin et al. (2008) recommended: providing the possibility to enlarge all the visuals, as this may be useful for people with low vision; translating the visuals into audio by describing the direction the player is going and notifying them of collisions through sound; providing different modes of navigation for the player's character, particularly, Trewin et al. (2008) proposed the use of a “find” command that tells players about nearby elements and a “controlled walk” command to walk towards a target identified via the “find” command. The suggestion of including these commands highlights the importance of providing exploration mechanisms in virtual worlds to people with visual impairment.

Atkinson et al. (2006) focused on guidelines to design meaningful earcons and auditory icons. Atkinson et al. (2006) prioritised the creation of earcons that: are time efficient, or as short as possible; are naturally grouped based on their function so that similar earcons convey similar actions and earcons that are distinctively dissimilar convey different actions. Additionally, Atkinson et al. (2006) argued that auditory icons could be used to increase fun through immersion and to imply information based only on the sound effect of choice, such as the use of gun sounds to convey danger in a shooter game.

In a twist to the approach of providing design guidelines for audiogames, Urbanek et al. (2018) proposed a series of “anti-rules” for audiogame design. These “anti-rules” are effectively things to avoid, and included: using sounds that are “painful to hear”;

punishing failure with loud sounds; using low-quality generic stock sounds; using sound that does not fit the in-game context; providing lengthy tutorials not accompanied by gameplay; using distracting music or ambient sounds or incomprehensible voice samples; not utilising the capabilities of sound for enabling the player to estimate spatial information, such as distance; mixing descriptive narration—the story-telling part of the gaming experience—with experiential narration, or the reading of in-game commands or controls; not being careful with the volume levels in the sound mix; and using auditory icons that are not related to the in-game action that triggers them, such as using the sound of a phone ringing when the player rings a doorbell.

Finally, Darin et al. (2017) studied how to conduct evaluations of multimodal games targeted to children with visual impairment. Darin et al. (2017) present a Standard Usability problem list describing the most common pitfalls faced when conducting this type of evaluation. The researchers identified that problems could be related to: *usability* (learnability, satisfaction and errors), *audio* (difficulty understanding earcons, poor relationship between sounds, actions and objects), *adaptability* (being unable to change the GUI of the games) and *mode and feedback* (difficulties using controllers and haptic devices). Interestingly, there is overlap between the problems identified by Darin et al. (2017) and the design guidelines presented more than ten years ago by Atkinson et al. (2006) and Trewin et al. (2008).

The design patterns described above focused on making the GUI of a game accessible, the design of earcons and auditory icons, and recommended the use of sound to convey spatial information. In this particular aspect, Trewin et al. (2008) suggested “find” and “controlled walk” commands. Although this approach certainly facilitates navigating virtual worlds, it does not provide a gaming experience that is equitably

accessible to that of sighted players (Smith & Nayar, 2018), as restricting players to navigate to specific targets only limits their agency and ability to wander around the virtual world. Hence, it is necessary to find a different alternative to use sound to convey spatial information. I propose looking at the physical world, particularly at echolocation, a technique some blind individuals already use in the physical world, to explore virtual environments.

### 2.4. Echolocation

Echolocation is a phenomenon that has been observed in several mammals, including dolphins, bats and some humans. Echolocation refers to the ability of these animals to use sound and echo reverberations to aid in the formation of a mental image of their surroundings to aid with exploration (Kolarik et al., 2014; Kupers & Ptito, 2014; Thaler, 2013).

Echolocation has fascinated scholars for hundreds of years. The first recorded account of an individual using echolocation dates back to 1749 and was made by Denis Diderot, chief editor of the French *Encyclopédie*, who wrote a letter entitled “Letter on the Blind for the Use of Those Who Can See.” (Margo et al., 2013). In it, Diderot described the life of Nicolas Saunderson, a blind mathematician, and argued that visual imagery is not fundamental for abstract thinking (Margo et al., 2013), while describing Saundersons’s ability “to perceive the presence of objects but also to judge accurately of their distance from him” (Supa et al., 1944).

In his letter, Diderot suspected that his acquaintance could perceive obstacles and estimate distance based on the change of air pressure around his face and increased

sensitivity in his facial nerves, hence echolocation was labelled “facial vision”. This name was accepted without question by the then-emerging scientific community and was used throughout the nineteenth century. Supa et al. (1944) provides the following summary of the understanding of echolocation—or rather, of facial vision—throughout the nineteenth century:

*“Zeune (1808) claimed that the blind used their cheeks and foreheads as “feelers;” Knie (1821) regarded air pressure as the stimulus; Sergel (1868) concluded from the results of his own experience, that “the distance sense” was clearest around the eyes and ears, weaker at the temples and on the forehead, still weaker on the cheeks, and almost lacking on the lips. Levy (1872) named this ability “perceptio facialis,” and described some remarkable feats that he himself could perform by means of his heightened facial sensitivity to minimal pressure stimulation<sup>2</sup>”*

Although the presumed stimulus that enabled blind people to detect obstacles was not what earlier scientists thought, the above paragraph demonstrates that the idea of “facial vision” captured the imagination of many. Moreover, the earlier accounts of “facial vision”, particularly Diderot’s original letter, helped change the perception Western society had of blind individuals, whom during the Middle Ages were seen as useless and perceived to be receiving divine punishment (Margo et al., 2013).

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<sup>2</sup> The original sources for Zeune (1808), Knie (1821), Sergel (1868) and Levy (1872) are hard to find. They appear in Supa, M., Cotzin, M., & Dallenbach, K. M. (1944). "Facial Vision": The Perception of Obstacles by the Blind. *The American Journal of Psychology*, 57(2), 133-183. <https://doi.org/10.2307/1416946> but are attributed to Burklen, K. (1924). *Blinden psychologie*. In *Blinden psychologie* (pp. 334-334).

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After centuries of using the term “facial vision”, a series of experiments at Cornell University, reported by Supa et al. (1944), Worchel and Dallenbach (1947), and Cotzin and Dallenbach (1950) demonstrated that blind people listened to the echoes of their own footsteps in order to detect obstacles. Thaler and Goodale (2016) explain that “the term echolocation was coined in 1944 by Donald Griffin, a physiologist at Harvard who was studying how some bats are able to avoid obstacles in the dark”. Even though the ability of blind people to avoid obstacles has been known for centuries, it is only over the last seventy years that we have begun to understand how this ability works.

The physiological mechanisms underlying echolocation have been studied and understood. Figure 2 depicts the process of echolocation, which is comprised of two stages: in the first stage, the echolocator produces a sound, usually with their cane or with their tongue. This sound travels and collides with nearby objects. Then, in the second stage, the echolocator listens to the reflections of the sounds they produced (Kolarik et al., 2014; Rowan et al., 2013; Thaler et al., 2017). Studies using fMRI have shown that the regions of the brain that process vision activate when an echolocator uses echolocation, thus supporting the theory of cross-modal neuroplasticity, which suggests that parts of the brain—specifically the parts in charge of processing images—are repurposed to process auditory signals in the brains of blind subjects (Kupers & Ptito, 2014; Thaler & Goodale, 2016).

There is a distinction between active and passive echolocation. During active echolocation, the individual actively produces sounds with their tongue, shoes, cane, fingers or by clapping, and listens to the reverberations produced by these sounds. During passive echolocation, individuals listen to the reverberations of sounds that occur naturally in the environment. For example, a passive echolocator may use the echo of a

ventilation fan in an office to gauge its size and the presence of obstacles (Ashmead et al., 1998; Stroppen & Pittenger, 1995). It is not clear whether echolocators prefer to use active or passive echolocation, or under what circumstances one would be more effective than the other. However, research has been conducted on the effectiveness of different sounds for active echolocation: Martínez Rojas et al. (2009) and Martínez Rojas et al. (2010) evaluated the usefulness of different sounds produced with the mouth and with one's fingers and found that a short and sharp clicking sound produced by hitting the tongue against the palate is the most effective sound for echolocation.

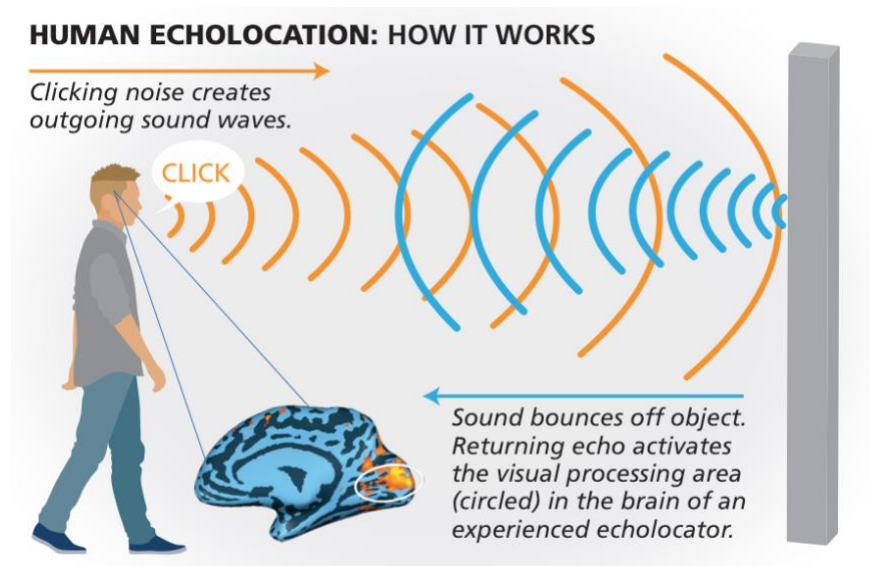


Figure 2. The process of human echolocation, Marlow and Brogaard (2015)

The physical characteristics of the sound wave generated when expert echolocators produce clicking sounds with their tongues has been thoroughly analysed and described. Unlike bats, who use sounds in ultrasonic sound frequencies above 20kHz, humans use sounds within the normal hearing range of 20Hz to 20kHz, as expected. However, there is evidence indicating that the sounds produced by echolocators contain strong frequency components in the higher part of the hearing spectrum (Rowan et al., 2013; Schörnich et al., 2012). Earlier studies suggested that the clicking sounds used by expert echolocators

have a duration of about 10ms, sound levels in the range of 60 to 108dB and maximum energy in the range of 6-8kHz (Kolarik et al., 2014; Schörmich et al., 2012). Kolarik et al. (2014) and Thaler and Goodale (2016) provide detailed spectrograms showing the frequency contents of mouth-clicks generated by expert echolocators.

Echolocators obtain information about their surroundings by processing minuscule differences in pitch and volume as the sound reaches each ear (Kolarik et al., 2014). Particularly, Schenkman and Nilsson (2011) found that pitch information may be more important than volume information for echolocation. A mathematical function that describes the minuscule differences in pitch and volume as sound reaches the ears is called a head-related transfer function (HRTF). HRTFs are dependent on the head, torso and ear geometry of each individual, and it is possible to obtain individualised HRTFs in an anechoic chamber with a HRTF measuring apparatus (Mehra et al., 2016). In contrast, generic HRTFs can be obtained by using a dummy head and two microphones on the side of the dummy head. The goal of using individualised HRTFs in virtual worlds is to provide a more realistic experience by providing a more accurate representation of how sound is perceived in the physical world. However, there are no studies analysing the use of individualised HRTFs and the use of echolocation in virtual worlds, and studies by Berger et al. (2018) and Poirier-Quinot and Katz (2018) suggest that the use of generic HRTFs is sufficient to perform auditory tasks that require precision, such as using sound to aim at a target in a first-person shooting game.

Both sighted and blind people can learn to echolocate. However, blind individuals outperform sighted blindfolded counterparts (Kolarik et al., 2014; Kupers & Ptito, 2014). Moreover, there are differences in echolocation capabilities within groups of blind individuals. For example, children born blind may develop echolocating skills without



the need for training (Ashmead et al., 1989; Kolarik et al., 2014), and people who lose their vision at a younger age show better performance than those who lose their sight later in life (Kolarik et al., 2014; Teng et al., 2012). This difference in echolocating abilities is one of the reasons why recruiting sighted individuals and blindfolding them will be avoided in this thesis.

### 2.4.1. Uses of echolocation

According to Thaler (2013) and Wallmeier and Wiegerebe (2014), people with visual impairment who can use echolocation have shown improved mobility and orientation skills in familiar and unfamiliar environments. Thaler and Goodale (2016) explain the features that echolocators can perceive that may give them an objective advantage when exploring their surroundings: “Blind echolocation experts can sense small differences in the location of objects, and can also differentiate between objects of various sizes and shapes, and even between objects made of different materials, just by listening to the reflected echoes from mouth clicks” (p. 382). Thaler and Goodale (2016) continue to argue that the ability to perceive these elements enable blind people “to do things that are otherwise thought to be impossible without vision, potentially providing them with a high degree of independence in their daily lives and demonstrating that echolocation can serve as an effective mobility strategy in the blind” (p. 382). As the advantages of being an echolocator become clear, researchers have produced physical aids that use a combination of sound and haptic feedback to allow non-echolocators to detect nearby obstacles (von Zabiensky et al., 2018; Watabe & Niitsuma, 2013).

An early study of the ability of echolocators to detect *distances from objects* was performed by Kellogg (1962), who conducted an experiment using a 30cm-wide wooden

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disk. In his experiment Kellogg (1962) moved the disk closer or further from participants, and found that a blind expert echolocator could detect changes in distance as small as 10cm and that sighted blindfolded individuals responses were not consistent enough to not be attributed to chance.

Rosenblum et al. (2000) also studied the use of echolocation to estimate *distance of moving and stationary objects*. In the experiment devised by Rosenblum et al. (2000), sighted blindfolded participants were required to “(a) echolocate a wall while either remaining stationary or moving; (b) stand motionless with occluded ears as the wall was moved away; and (c) walk to the position where the wall had been during their echolocation” (p. 185). Participants underwent a training stage where feedback was provided, and they were encouraged to try different echolocating sounds. Rosenblum et al. (2000) found that participants were comparatively more successful at echolocating a wall when they were allowed to move. The findings made by Rosenblum et al. (2000) support the idea that sighted individuals can learn to echolocate, that moving may provide additional spatial cues when compared to remaining stationary, and update previous findings by Kellogg (1962), who had found that sighted blindfolded individuals’ performance in detection tasks was attributed to chance.

A study conducted by Milne et al. (2015) investigated the ability of a blind expert echolocator to consistently identify the *size of objects* perceived through the use of echoes. Milne et al. (2015) conducted their experiment with a blind expert echolocator, ten blind individuals and ten sighted blindfolded subjects, using both groups as controls. To estimate size of objects, participants were presented with either a small, medium or large wooden circle, or a small, medium or large rectangle, positioned at a distance of 80cm from the participant. Milne et al. (2015) found that the expert echolocator

performed significantly better than the control groups when discerning the size of objects. The ability of expert echolocators to identify size of objects, Milne et al. (2015) argue, is valuable when a blind individual explores an unfamiliar space, as it may help avoid collisions.

While Milne et al. (2015) shed light on the ability of an expert echolocator to judge the “real” size of an object, Teng and Whitney (2011) compared the ability of a group of eight sighted blindfolded individuals versus a blind expert echolocator to differentiate “*acoustic*” size of objects. Thaler and Goodale (2016) explain that acoustic size “can be defined as the acoustic angle an object subtends” (p. 385). Hence, acoustic size refers to the position of an object relative to the horizontal line of sight (or hearing) of a person. This angle is also known as azimuth. Teng and Whitney (2011) conducted an experiment where participants sat 33cm away from a set of two round disks that were placed at different heights from the participants’ line of sight (i.e. placed at different azimuth angles), and found that, although the blindfolded individuals quickly learnt to estimate differences in acoustic size with a precision of 17 degrees, the blind subject could detect changes as small as 8 degrees at a distance of 75cm. This supports the claim that expert echolocators outperform sighted blindfolded control individuals.

Hausfeld et al. (1982) and DeLong et al. (2007) investigated whether echolocation could help identify the *material* certain objects were made of. DeLong et al. (2007) recruited a group of sixteen sighted blindfolded individuals and devised a two-task experiment. The first part of the experiment investigated whether participants could identify a “standard” hollow cylinder versus a hollow cylinder with walls of  $\pm 0.2$ , 0.3, 0.4 and 0.8mm of thickness. The second part of the experiment investigated whether participants could use echoes to identify the presence of spheres made of: steel, brass,

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aluminium, nylon and glass. DeLong et al. (2007) found that participants could discriminate the standard cylinder from the thicker or thinner cylinders with an accuracy of 97.1% and could identify the material of the spheres with an accuracy of 86.6%. These results are very positive, especially considering that the participants were untrained and sighted.

The last aspect that has been investigated about echolocation is its usefulness for detecting *obstacles and immediate collisions*. Some of the earlier research on echolocation proper, by Supa et al. (1944) investigated this phenomenon. Supa et al. (1944) compared a blind individual with two sighted blindfolded controls and found that the blind individual could successfully stop before running into a wall and could orient themselves to walk in a straight line, whereas the blindfold subjects ran into the wall several times and had significant trouble walking on a straight line. However, Supa et al. (1944) detected that, after initial errors, blindfolded subjects learnt how to detect the wall. Once again, this supports the argument that, even though sighted blindfolded individuals can learn how to echolocate, blind subjects outperform them.

In this section, I have summarised the use of echolocation to detect obstacles and collisions, distance, shape, thickness and material of objects. Methodologically, a common trend has been the recruitment of a minority of blind individuals together with sighted blindfolded individuals. The result is that the blindfolded participants can learn to detect the desired feature, but blind subjects outperform them. The findings in this section provide a thorough understanding of echolocation in the physical world: what it is and how it is used. Building on this knowledge of echolocation, researchers have developed implementations of echolocation in virtual worlds. These implementations are discussed in the following section.

#### 2.4.2. Echolocation in virtual worlds

The previous sections described how echolocation is understood in the physical world. As computers and virtual worlds became more ubiquitous, there have been attempts to create computational representations of echolocation. One of the first attempts to recreate echolocation with a computer system was developed by Ramos and Arias (1997), who implemented *ECOTEST*. This system combined a 12-bit sound card, a custom software written in Borland C++ to interface with the sound card, and the Waveform Generation Language (WGL), which was a custom programming language that allowed users to create and capture auditory signals. The apparatus created by Ramos and Arias (1997) was the first attempt at providing artificial echolocation through the use of differences in pitch of artificial sounds. The apparatus was tested by Arias and Ramos (1997) with 30 sighted individuals and one blind person. Arias and Ramos (1997) found that the blind individual performed better than the sighted counterparts when required to identify repeated pitches. This may suggest that, even in virtual worlds, blind individuals outperform blindfolded sighted subjects.

Another implementation of echolocation was described by Pelegrin Garcia et al. (2014). The authors built a custom-made system that enhanced the existing capabilities of the commercial software *CATT Acoustic*, which is used to model the acoustic design of architectural spaces, by letting participants use self-generated sounds captured with a microphone, and adding a model of the near-field propagation of the sound from the mouth to the ears to the output generated by *CATT Acoustic*. The resulting signal was then communicated to participants via headphones with head-tracking capabilities. The approach presented by Pelegrin Garcia et al. (2014) aimed to provide a realistic

reproduction of echolocation in a virtual world and found that for expert echolocators, “while the system reacts smoothly and has a pleasant sound, it does not reproduce accurately the sensations of sound reflections occurring at close distances”. This suggests there is an aspect of echolocation that is difficult to capture and replicate in virtual worlds.

Similar to Pelegrin Garcia et al. (2014), Picinali et al. (2014) used the commercial software *CATT Acoustic* as foundation to model a virtual environment after a location in the physical world. In fact, Picinali et al. (2014) offer one of the very few studies exploring the use of echolocation in virtual environments to support the acquisition of spatial knowledge. Most importantly, the authors trialled their system with a virtual reality headset and found the additional head tracking capabilities provided by the headset improved participants’ opinion of the overall experience and enabled participants to reconstruct the virtual spaces—which was modelled after a real-world location—as accurately as if participants had physically explored the virtual space.

Schörnich et al. (2012) presented a different approach to echolocation in virtual worlds. The authors used a microphone to capture clicking sounds produced by participants, convolved them with individual HRTFs and played the newly generated audio signal back to participants through headphones, thus simulating echolocation as it would occur in the physical world. In their experiment with five test subjects, Schörnich et al. (2012) found that individuals can be successfully trained to detect changes in the distance of an object in an echolocation-enabled virtual space.

Another experiment involving training of subjects in virtual echolocation was conducted by Robinson and Kearney (2016). The researchers’ goal was to create an echolocation-enabled virtual environment to train people in echolocation, particularly focusing on the detection of walls and the estimation of distances to said walls. To this

aim, Robinson and Kearney (2016) used the commercial tool *MAX/Msp* to convolve pre-recorded white noise with head-tracking information and customised HRTFs and conducted an experiment where 16 participants sat in an anachronic chamber and were required to detect direction and distance to the closest virtual wall. The experiment included training. The authors' results show that participants' performance in detecting direction and distance of virtual walls improved after receiving training.

Another experiment where the aim was to teach participants how to use echolocation was conducted by Wu et al. (2017). In this experiment, Wu et al. (2017) used the game-development software *Unity* and pre-recorded clicks to produce a series of two-dimensional maze-like levels. In these levels, participants moved in a grid-like pattern, avoided obstacles and were required to find an exit. The pre-recorded clicks were processed to simulate them bouncing off the virtual walls. Wu et al. (2017) received initial qualitative feedback on their system by six blind individuals who used the technology for ten to fifteen minutes and used these comments to inform their final design. Finally, the system was evaluated by eight sighted individuals and the results were reported by Heller et al. (2017), who ran a pre and post evaluation, asking participants to detect distance to a wall in the physical world before and after training with the system. Results showed improvement in participants' ability to detect the presence of walls in the physical world after approximately fifteen hours of training, thus suggesting that it is possible to learn to use echolocation in virtual worlds.

Andreasen et al. (2018) tested the feasibility of using freely available software for the creation of echolocation-enabled virtual environments. In their experiment, Andreasen et al. (2018) explored the concept of "virtual body ownership" by asking participants to embody a bat in a virtual world and use echolocation to explore said world.

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Participants were asked to explore the virtual environment under four different conditions—but always embodying a virtual bat: one condition included visual navigation of a cave-like virtual space, and the remaining three conditions used different aural settings. Andreassen et al. (2018) considered their study to be a prototype evaluation and concluded that the use of the freely available software *Unity* and the plug-in *SteamAudio* provided a level of simulation of sound reverberation over virtual surfaces good enough to be used in echolocation scenarios.

The literature shows that several attempts have been made to use virtual worlds to teach echolocation. Learning echolocation in a virtual world is seen as safer than learning it in the physical world, and learning this skill is conducive to better orientation and mobility outcomes (Connors et al., 2014; Thaler, 2013). However, previous studies have had several limitations. Preliminary studies such as those conducted by Wu et al. (2017) and Andreassen et al. (2018) suggest that freely available tools such as *Unity* are adequate to creating echolocation-enabled virtual environments; however, due to the preliminary nature of these studies, it is not clear how echolocation could be used beyond experimental feasibility tests. Experiments that focus on recreating echolocation in virtual worlds as accurately as it occurs in the physical world (Pelegrin Garcia et al., 2014; Picinali et al., 2014; Schörnich et al., 2012) are limited by the need to use proprietary software, the computational complexity of such approaches, and sometimes the need for highly specialised equipment or setups that may be difficult to recreate outside the laboratory. Although some of these experiments have focused on identifying the presence of walls, echolocation has the potential to enable detection of materials (DeLong et al., 2007; Hausfeld et al., 1982), size of objects (Milne et al., 2015), and other characteristics. All these features support people with visual impairment in exploring their surroundings



in the physical world; however, the features that can be detected in virtual worlds via echolocation remain largely unexplored. Finally, the reliance of these experiments in sighted blindfolded individuals makes it difficult to ascertain whether echolocation in virtual worlds is useful for people with visual impairment. As Silverman (2015) states, the experience of blindfolding a subject successfully replicates the initial shock of losing a sense, but it fails to capture the set of unique skills people living with visual impairment have developed through their lived experience.

Hence, very little is known about how echolocation in virtual worlds may support people with visual impairment in freely exploring these worlds. A key factor to successfully exploring any space, be it virtual or physical, is being able to acquire spatial information (Façanha et al., 2020). The following section describes the types of spatial information available, and how spatial knowledge can be assessed.

### **2.5. Acquisition of spatial information**

Spatial information comprises the understanding of one's surroundings. Acquiring spatial information to navigate the world is a critical skill that people with visual impairment need to undertake in order to live more independent lives (Kitchin & Jacobson, 1997). It has been argued that sight is necessary to acquire spatial information, particularly as brain scans revealed that people who become blind earlier in life process non-visual spatial information in regions of the brain that are different from those of sighted individuals (Thinus-Blanc & Gaunet, 1997). However, this does not indicate that people with visual impairment cannot acquire spatial information. Other sensory input, such as auditory feedback, may be used to acquire spatial information (Cuturi et al., 2016), and the brain may adapt itself to using a different type of stimulus to understand space in a process

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called cross-modal neuroplasticity (Bavelier & Neville, 2002; Kupers & Ptito, 2014; Schinazi et al., 2016).

Spatial information has been classified into three categories, according to their level of complexity: landmark, route and mental maps—also referred to as survey knowledge (Kitchin & Jacobson, 1997; Loomis et al., 1993; Siegel & White, 1975). The next sections provide a short description of each type of spatial knowledge: landmark, route and survey, and how they relate to each other.

### 2.5.1. Landmark knowledge

Landmarks are specific objects placed in specific locations that may be used as points of reference along a route (Caduff & Timpf, 2005; Werner et al., 1997). Werner et al. (1997) argued that the identification of landmarks and its use for navigational purposes is an elementary navigation task, as landmarks are minimal elements for representing space (Siegel & White, 1975). Moreover, landmark navigation has been found to be more effective than navigating the physical world by relying on memorising street names or estimating distances (Caduff & Timpf, 2005). When considering how people with visual impairment identified landmarks, Werner et al. (1997) argued that stable, fixed and persistent objects—such as walls, door openings, lamp posts—may be used as reliable landmarks.

### 2.5.2. Route knowledge

A route is the union of several static points of information—landmarks—in a fixed, sequential set of steps that indicate how to reach a destination. When using routes for

navigation, the alteration of any one step along the route may leave a person with visual impairment stranded (Darken & Sibert, 1996; Thinus-Blanc & Gaunet, 1997). Moreover, people with visual impairment are known to stick to familiar routes to avoid getting lost, even if these routes are longer and less efficient, provided that they were easier to describe and follow (Caduff & Timpf, 2005; Kitchin & Jacobson, 1997; Thinus-Blanc & Gaunet, 1997; Werner et al., 1997)

### 2.5.3. Survey knowledge

Survey knowledge provides a holistic understanding of the physical environment that emerges as the result of encoding several routes and landmarks so that the product of this combination provides a more flexible understanding of the environment (Thinus-Blanc & Gaunet, 1997). Survey knowledge provides a mental image or a “mental map” of one’s surroundings (Cuturi et al., 2016). Forming a mental map is a neurological process, but the image that forms in one’s head is not that of a literal map, but rather a series of interconnected, more manageable pieces of spatial information (Siegel & White, 1975).

In order for people with visual impairment to explore the physical world and form a mental map of their surroundings, they must rely on a mobility aid. The most common mobility aids used by people with visual impairment are white canes and guide dogs, with people who rely on guide dogs showing more confidence when exploring their surroundings (Clark-Carter et al., 1986). Another aid that helps people with visual impairment to acquire survey knowledge is echolocation and its usefulness has been described in previous sections of this chapter. However, this technique is used by a rather small portion of people with visual impairment (Thaler, 2013).

### 2.5.4. Evaluating spatial knowledge

Kitchin and Jacobson (1997) have proposed the use of the following techniques to evaluate spatial knowledge: route inference; distance estimation; direction estimation; completion tasks—where participants may use and complete a map with tactile elements; reconstruction tasks—where participants are asked to build a model of the environment, be it by drawing or using a specialised material; and recognition tests—where participants are given a model of the environment and are asked to identify specific features. Kitchin and Jacobson (1997) argue that there are issues of validity surrounding the evaluation techniques listed above and that “the utility of someone's knowledge is best assessed through tasks that demonstrate it in action, such as wayfinding in a complex environment” (p. 367). However, the authors recognise that this may be impractical in certain settings and recommend using a mix of the techniques described earlier to ensure spatial knowledge is consistent.

There are several examples of the use of reconstruction tasks in the literature, both in the physical world and in virtual environments. In the physical world, Watabe and Niitsuma (2013) required sighted blindfolded participants to use a vibrating device to detect walls of a particular layout, then remove the blindfolds and draw the layout they had explored. Albouys-Perrois et al. (2018) used a combination of foam paper, modelling clay and pipe cleaners for the modelling of low-fidelity tactile map prototypes. Holloway et al. (2018) used recognition tests, where blind participants were given two models and asked about specific features of both models. In virtual spaces, Lahav and Mioduser (2008) proposed the creation a virtual environment that provided haptic feedback, and Lahav et al. (2012) evaluated said environment by asking participants to perform

completion tasks with a kit of pieces representing the layout they had to explore. With less emphasis on acquisition of spatial knowledge in virtual worlds, it is hard to know if the techniques described by Kitchin and Jacobson (1997) would be as effective as they are in the physical world. Darken and Sibert (1996) argued that “survey knowledge is the key to successful wayfinding in any environment” and recommended dividing large virtual worlds into distinct, smaller parts and providing constant orientation cues. The idea of dividing space into smaller parts has been used to provide access to spatial information in digital worlds (Ghali et al., 2012). However, regarding the provision of constant orientation cues, less is known.

Existing literature on echolocation in the physical world has described how it can be used to learn about discrete—landmark—features of physical space, such as material of objects, distance from and presence of obstacles (DeLong et al., 2007; Hausfeld et al., 1982; Rosenblum et al., 2000; Schörnich et al., 2012; Supa et al., 1944). Moreover, the fact that expert echolocators perform better in orientation and mobility tasks in both familiar and unfamiliar spaces suggests echolocation is also useful for acquiring survey knowledge of space (Thaler, 2013; Wallmeier & Wiegerebe, 2014). However, it is not known if this utility is applicable in virtual spaces.

### **2.6. Research Gaps**

As the previous sections demonstrate, the process by which people with visual impairment understand and negotiate their surroundings in the physical world is well understood. Landmarks, routes and mental maps are the pieces that enable people with visual impairment to make sense of the environment around them. Additionally, echolocation, the mechanisms that underpin it and its role in the acquisition of spatial

information have been well understood. The literature also describes how people with visual impairment engage with mainstream games, text-based adventures and audiogames. Despite the clear usefulness of echolocation in acquiring spatial knowledge in the physical world, its role in virtual worlds and how it can support the acquisition of spatial knowledge in these worlds remains an under explored subject, with research in this field focusing on detection of virtual walls and evaluations relying mostly on blindfolded sighted individuals. Therefore, I propose to investigate the following research question:

*How can echolocation be designed as a means for people with visual impairment to acquire spatial knowledge of a virtual space?*

Virtual space is a broad construct that refers to the simulated space where any type of digital experience occurs; this includes videogames, and virtual and augmented reality experiences. In order to answer the main research question, it is necessary to first understand how people with visual impairment currently engage with existing virtual spaces. As this chapter demonstrates, there are several digital experiences targeted to people with visual impairment in the form of text-based adventures and audiogames. However, often times the analysis of these digital experiences focuses on the introduction and evaluation of a single digital experience and not much is known about how people with visual impairment engage with these experiences “in the wild” outside the context of a laboratory evaluation. Hence, I will aim to explore the following sub-research question:

**RQ1:** How do people with visual impairment currently engage with virtual spaces?

A key element to enable engagement with digital experiences is being able to explore the virtual space. By looking at the physical world, this chapter argues that echolocation is a useful tool to aid in this process of acquiring spatial information. Moreover, this chapter describes existing implementations of echolocation in virtual worlds and indicates that the usefulness of echolocation to learn about spatial information in virtual worlds remains under explored. With this in mind, the next step of this thesis will be to explore if it is possible at all to replicate echolocation in a virtual setting so that it supports acquisition of spatial information, thus answering the following sub-research question:

**RQ2:** How can echolocation be implemented in virtual worlds so that it supports acquisition of spatial knowledge?

This chapter has described how echolocation is used in the physical world to assist in the identification of landmark features of space—size of objects, the material and object is made of, distance, and presence of obstacles. These features aid people with visual impairment in the formation of mental maps. Upon identifying a baseline on how to implement echolocation in virtual worlds to support acquisition of spatial knowledge, the next sub-research questions aim to expand this knowledge, starting by identifying:

**RQ3:** What features of virtual space can be revealed through echolocation?

Landmark features of virtual space are used to create a mental map of the space being explored in the physical world. Upon identifying the features of virtual space that can be revealed through echolocation in virtual worlds, the next sub-research question will address:

**RQ4:** How do the features revealed through echolocation support acquisition of spatial knowledge of virtual space?

As previous research has found that not including people with visual impairment in the process of designing technologies targeted to them leads to abandoning these technologies (Phillips & Zhao, 1993), it is important for the implementation of echolocation developed as part of this thesis to be informed by the views of people with visual impairment. Furthermore, the next chapter will explain the importance of the lived experience of people with visual impairment for this work. With these considerations, the last research question to be explored will be:

**RQ5:** How can a co-creation process inform the design and implementation of echolocation in virtual spaces?

The answers to the five sub-research questions identified above will inform the answer to the main research question of this thesis. Moreover, by answering the research questions presented in this section, it is my aim to help bridge the gap between academic literature and the game development industry by presenting a tool that supports access of people with visual impairment to digital games, provides an enjoyable experience, is easy to implement, and whose design has been informed by people with visual impairment themselves.

### 2.7. Summary

In this chapter, I have described accessibility in digital games and how this topic is approached from the perspective of the evaluation of a single accessible game. I have explained what echolocation in the physical world is, how it supports acquisition of



features of space (material an object is made of, presence of obstacles, size of objects, distance from objects) and how its use results in better orientation and mobility outcomes. Moreover, I have argued that, although current implementations of echolocation in virtual worlds exist, how these implementations could support acquisition of spatial information in virtual worlds is a phenomenon that remains unexplored.

As described in the introductory chapter of this thesis, I will focus on the use of echolocation to acquire spatial knowledge of virtual space. By doing so, I aim to conduct a design exercise that recognises the unique skills of people with visual impairment. In the following chapter, I describe the theoretical framework and methodology that support the work to be carried out as part of this thesis, starting with the worldview that informed this research, then presenting the design of the research and the methods to be used.



# Chapter 3: Methodological Framework

## 3.1. Introduction

Chapter two discussed previous work in the fields of spatial information acquisition, gaming for people with visual impairment, and echolocation, and highlighted a series of gaps that exist in these fields. In this chapter, I present the philosophical orientation that will inform the way in which I will address the existing gaps and the research questions that emerged from these gaps. I will articulate my views on what exists in the world (ontology) and how we gain knowledge about what exists in the world (epistemology). My epistemological discussion will centre around the different paradigms that exist to understand disability and how HCI has incorporated these paradigms to inform the design of assistive technologies. Finally, I will outline the methodology and methods of choice to conduct my research, as these stem from my ontological choices.

This chapter is heavily influenced by the book “*Disabilities Rights and Wrongs Revisited*” by Tom Shakespeare (2013). The first edition of “*Disabilities Rights and Wrongs*” was published in 2006 and was considered controversial, even treasonous (Goodley, 2014), as it strongly criticised existing worldviews on disability, called other authors to leave behind the rejection of the biological dimension of disability, and

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exhorted them to operationalise the concepts they had been debating for years so that disability could stop being an issue of discourse and become a more practical matter (Goodley, 2014). Despite the criticism the book has received, I found that Shakespeare's views on the concept of disability align heavily with my own lived experience of disability, and my previous experience working with people with visual impairment, which I described in chapter one.

In this chapter, I describe the four theoretical constructs that act as foundation for this study using a research framework outlined by Creswell and Plano Clark (2011): worldview, theoretical lens, methodology, and methods. I present a pragmatist worldview that leans on critical-realist disability studies as a lens to describe the problem of accessibility in digital games for people with visual impairment. I propose the use of mixed methods to answer the research questions presented in the previous chapters and describe some of the tools used for data collection under the outlined constructs.

This chapter is structured as follows: I start by defining pragmatism as my worldview and describe why I chose this instead of other worldviews more associated with qualitative traditions (postpositivism) or with quantitative traditions (constructivism) (section 3.2). Then I explain the different lenses under which our understanding of disability has been constructed: the medical model (section 3.3.1), the strong social model (section 3.3.2), the model proposed by cultural disability studies (section 3.3.3), and Tom Shakespeare's model of critical-realist disability studies (section 3.3.6). As I describe each lens, I explain how it may be of use to HCI researchers. This chapter also includes a discussion about the language I will use throughout the rest of this thesis when referring to participants and in general, to people with visual impairment (section 3.3.4). I then discuss how the critical realist lens relates to HCI via the "critical

realist agenda for assistive technology” proposed by Frauenberger (2015) (section 3.4) and explain how my research aligns with that agenda. Finally, I describe the methodology that I will adopt to answer my research questions, the methods and tools used to find these answers (section 3.5), and how these stem from my theoretical orientation.

### **3.2. Worldview**

As Creswell and Plano Clark (2011) highlight, “all research has a philosophical foundation, and enquirers should be aware of assumptions they make about gaining knowledge during their study” (p. 38). Hence the importance of presenting these assumptions early on and describing how they impact the development of the research endeavour. The first assumption that a researcher must declare is about reality and the things that exist within it. This is what is known as ontology. The assumptions a researcher makes about reality ultimately inform the methodology that is applied in the research enquiry.

Creswell and Plano Clark (2011) and Denzin and Lincoln (2011) identify three worldviews that may inform scientific enquiry: postpositivism, constructivism and pragmatism—though these are not the only worldviews that exist. Postpositivism argues that reality is objective, measurable and can be known through empirical means. Postpositivism has largely influenced the way in which science has been performed over the last two hundred years or so (Frauenberger, 2015). Subscribing to a postpositivist view means that one believes that, to find the truth about a phenomenon being investigated, it is necessary to devise an experiment that provides a quantifiable measure about the phenomenon under investigation. This worldview may be more suitable for studying phenomena of the physical world.

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In contrast to postpositivism, constructivism argues that reality is subjective and is constructed upon the social circumstances of each individual (Denzin & Lincoln, 2011). Furthermore, some thinkers view constructivism as being in total opposition to postpositivism, with Denzin and Lincoln (2011) describing constructivism-inspired research as “an ongoing critique of the politics and methods of postpositivism” (p. 7). The social sciences, arts and humanities are fields with strong constructivist traditions.

Disability and designing technology in the context of disability is a complex, multidimensional problem that does not present a unique solution. With this consideration in mind, I would argue for the need of a worldview that allows for the conceptualisation of a complex reality that is comprised of both subjective experience and objective factors (Creswell & Plano Clark, 2011). This is: to understand the design of technology in the context of disability, I believe, like Shakespeare (2013), that there is a need for more empirical studies in the field (suggesting allegiance with a postpositivist worldview). However, just like Shakespeare (2013), I also believe that the experience of disability is unique to each individual—as I expressed in chapter one—with individuals with the same impairment and in the same cultural context having an entirely different experience of disability (suggesting a constructivist allegiance). Therefore, the work presented in this thesis needs to be supported by a worldview that is congruent with my understanding of reality. Pragmatism is the worldview that best reflects my position.

According to Teddlie and Tashakkori (2003), as explained by Creswell and Plano Clark (2011, p. 43), a pragmatist worldview recommends abandoning the force-choice dichotomy between postpositivism and constructivism, and advises to give primary importance to one’s research question(s), observing the methods that would best help answer the research question(s). The implications of such a worldview are that

methodological choices should be guided by practical considerations as well as philosophical theories, and that both quantitative and qualitative research methods may be used.

This seemingly “everything goes” approach encouraged by a pragmatist worldview has received criticism. Denzin and Lincoln (2011) argue that a pragmatist worldview encourages a more postpositivist way of thinking and discourages the use of more interpretative methods. Moreover, Creswell and Plano Clark (2011, pp. 278-280) warn that the different approaches followed in studies that align with other worldviews—with postpositivist studies barely discussing the philosophical underpinnings of their method of choice, and constructivist studies making these philosophical underpinnings key points of the studies—may make it difficult for the pragmatist researcher to know how to approach the discussion of their worldview. Additionally, Morse and Niehaus (2009) warn that the ad-hoc mixing of research methods may be a serious threat to validity. Despite these criticisms, I believe that a pragmatist worldview, with its focus on “employing ‘what works’, using diverse approaches, and valuing both objective and subjective knowledge” (Creswell & Plano Clark, 2011, p. 43) aligns perfectly with my own conceptualisation of the world and knowledge in it, hence my choice for a pragmatist worldview. Moreover, this worldview provides a solid foundation for the critical realist lens used in this work, to be explained in following sections.

### **3.3. Theoretical lenses to understand disability**

Over time, different lenses have been applied to construct our understanding of disability, from the medical model to the strong social model, the cultural disabilities studies, and the critical realist model. These models reflect the evolution of the ways in which we

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think about disability, and in this section, I will briefly describe them. Moreover, I will describe how my pragmatist worldview particularly aligns with the critical realist lens, as described by Shakespeare (2013), and describe the implications of this alignment for my research.

### 3.3.1. The medical lens

Our understanding of visual impairment and blindness has evolved over time. During the Middle Ages, blindness was seen as a “cruel fate”, as blind people could not participate in manual labour, thus remaining isolated, becoming beggars or objects of derision; a sector of the population even considered blindness a divine punishment during these times (Margo et al., 2013; Weygand, 2009). This view of blindness endured until the 18<sup>th</sup> century. During that century and thanks to the opening of the first schools for the blind and the invention of the Braille writing system the blind could start to actively participate in society in meaningful ways (Margo et al., 2013).

As we moved further into the era of the industrial revolution, advances in medicine improved overall health conditions, reduced mortality rates and extended life spans. It was into this climate that the medical model of disability emerged. Moser (2000) describes this model as being characterised by “normalisation”, where “an able-bodied and competent person is thus a body with a set of given functions, skills and properties” (p. 205). In this context, disability—in our case visual impairment—is seen as a *loss of function*, or a *diminished ability to function* and the role of any intervention targeted to people with disabilities must be to rehabilitate, recover and normalise their functioning (Moser, 2005).



Moser (2000) warns that the problem with this approach is that “disabled people are destined to be substandard within this normalization regime. They will always be constituted in contrast to a norm, they will always be defined as Other” (p. 209). More practically, Brisenden (1986) warns that this understanding of disability is detrimental, as it undermines the validity of the opinions of people with disability—it undermines the validity of the *lived experience* of disability, in favour of the voices of medical experts, who focus on hard facts but overlook the subjective reality of the lived experience.

It may be tempting for HCI researchers to use the medical lens to justify technology interventions aimed at people with impairments, as this lens lets researchers focus on a set of requirements for design based on the physical limitations of the individuals (Frauenberger, 2015; Mankoff et al., 2010). However, it is necessary to acknowledge that such an approach reinforces the idea of positioning people with disabilities as “Others” who need to be normalised. As this lens dismisses the value of the subjective lived experience of disability, it is not compatible with a pragmatist worldview.

### 3.3.2. The strong social lens

The strong social lens is also called the social creationist lens by Oliver (1990). The most salient feature of this lens is a clear separation between the concepts of impairment and disability. According to Shakespeare (2013), this distinction between the impairment and disability was a simple but powerful one, to the point that it was called “the big idea” of the disability movement in the 70s (Hasler, 1993). To indicate how important this distinction between impairment and disability was, Shakespeare (2013) states that “The term social model has become synonymous with progressive approaches to disability, while the term 'medical model' sums up everything that is backward-looking and

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reactionary” (p. 11). Shakespeare’s comments highlight the significance of the social lens in the context of how disability was understood.

The operationalisation of the difference between impairment and disability is best summarised with the publication of the policy statement of the Union of Physically Impaired Against Segregation (UPIAS) in the United Kingdom in the 70s. The policy statement read:

*“In our view, it is society which disables physically impaired people. Disability is something imposed on top of our impairments, by the way we are unnecessarily isolated and excluded from full participation in society. Disabled people are therefore an oppressed group in society” (UPIAS, 1976).*

This statement has several implications: first, it forces a dichotomy between impairment and disability and separates the two ideas, positioning impairment as a statement of the body’s function and disability as a function of social norms and biases; second, it places the limitations associated with impairments outside of the control of the individual; and third, it establishes disabled people as an oppressed group. (Shakespeare, 2013). Furthermore, the impairment/disability dichotomy can be thought of as a parallel to the sex/gender dichotomy presented in the seminal feminist work of Anne Oakley (1972), as both dichotomies place an idea—be it “disability” or “gender”—outside the individual, and formalise it as a social construct. Future sections explore why it may not be wise to extend these parallels too far.

A consequence of this approach to disability was in the way disabled people thought about themselves. According to Shakespeare (2013, p. 13) “rather than feeling sorry for

themselves, disabled people could feel angry” because they or their bodies were not at fault, but rather society and the exclusive approaches that were followed. A second consequence of this approach was a transition away from treatment and rehabilitation—as mandated by the medical tradition—to a focus on policy and barrier removal, with bills such as the Americans with Disabilities Act of 1990 being the prime example of the perceived success of this approach (Shakespeare, 2013).

Similarly, in the technology space, an example of this barrier-removal approach is the Web Content Accessibility Guidelines (WCAG), published by the Web Accessibility Institute (WAI). These guidelines provide recommendations on how to make websites more accessible for everyone, although the majority of these recommendations are easier to implement to improve accessibility of people who are blind or visually impaired (Frauenberger, 2015).

Although this strong social lens approach has produced benefits to people with disabilities, such as the Americans with Disabilities Act and the WCAG guidelines, Shakespeare (2013) makes a number of criticisms to this approach. Crucially for my own argument, Shakespeare recognises that no amount of barrier removal can equate the lived experience of disabled and non-disabled persons. In the case, for example, of patients with chronic pain or who have suffered a stroke, the social model approach fails to capture the complexity of the experience of these patients (Lock et al., 2005).

Although my approach to studying accessibility in digital games for people with visual impairment may be considered a way of removing barriers, I do not see it as such. A barrier-removal approach to digital games would possibly take the form of guidelines and specific features put forward by industry leaders. I argue that I have not developed a

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feature, but rather I aim to develop a new gaming metaphor for people with visual impairment.

### 3.3.3. The cultural disability studies lens

The cultural disability studies lens is referred to as the social constructivist model by Oliver (1990). This name hints at the constructivist philosophical worldview behind the model. The main changes this lens proposed were “a focus on embodiment, awareness of the cultural imagery, deconstruction of binary thought in favour of fluidity of all categories, and a recognition of the importance of emotion and affect” (Shakespeare, 2013, p. 47). This means that, under a cultural disability studies lens, there is a shift from “cure to care” (Zola, 1983) while at the same time scrutinising the way in which disability is portrayed—constructed—in society. This lens highlights the role of discourse in our collective conception of disability (Shakespeare, 2013), thus recognising that disabled bodies—just like female or dark bodies—should not be seen as incomplete, vulnerable or incompetent (Goodley, 2001). The goal of this lens is to give a minority group “voice in academic work that may otherwise be done *about* them but not necessarily *with*<sup>3</sup> them” (Mankoff et al., 2010). This goal highlights the importance of having researchers with disabilities, like myself, doing research in the field, and the relevance of engaging with and giving voice to people with disabilities. In practical terms, this discourages the recruitment of participants without disabilities in studies of technologies for people with disabilities; I will come back to the issue of participants in later sections.

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<sup>3</sup> Original emphasis of the author

This view further advances parallels between issues of disability, sex and race. However, Shakespeare (2013) warns that extending such parallels too far may be detrimental to the life of people with disabilities. According to Shakespeare (2013, p. 49), “gender, race and sexuality have minimal biological underpinning. However, disability always has a biological dimension that usually entails limitation or incapacity, and sometimes fatality and pain”. In other words, if we removed all the socially-constructed limitations built around sex, gender or race, these characteristics would become neutral; however, no amount of discourse analysis and societal deconstruction will ever negate the fact that—unlike sex, gender or race—disability is not neutral: it entails “limitation and incapacity, and sometimes fatality and pain”.

Shakespeare (2013) goes further in his criticism of this model and posits that “cultural disability studies writers generally seem much more interested in texts and discourses than in the ordinary lives of disabled people” (p. 52) and that these authors extend their ideas into potentially dangerous territory. Shakespeare (2013) cites Goodley (2011) as an example of an author who places a stronger focus on discourse over the practicalities of living with disabilities. Goodley (2014) argues that the cultural change in perception of the capabilities of people with Down Syndrome over the last eighty years implies that the disease is just “a phenomenon created through signification” (p. 117). Shakespeare counters that, although societal attitudes towards people with Down Syndrome have changed over time, the disease has always been and continues to be a consequence of an extra copy of the chromosome 21.

Another way in which this lens may result in detriment of the lives of people with disabilities is by underplaying the importance of diagnosis and treatment (Mankoff et al., 2010; Oliver, 2005). Cultural disability authors such as Tremain (2001) argue that

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diagnosis is something malign, as it attaches a label to a person and their condition: “congenital”, “acquired”, “sensory”, “cognitive” impairment, et cetera. Others such as Goodley (2011) suggest that disability is “concocted” by schools, hospitals and other institutions: if these institutions disappeared, disability would stop being a problem. As someone born with a congenital eye condition that needed to be diagnosed before I could talk and “engage with discourse”, I see these labels that Tremain (2001) criticises as something useful, as they assisted my parents in choosing care options. Moreover, I find it hard to believe that my congenital condition may have been caused by societal institutions, as congenital conditions are developed while the baby is still in the womb. I cannot see how elimination of certain institutions would affect foetal development. Hence, based upon my lived experience, I find that I cannot agree with these notions.

To summarise: the cultural disabilities movements has lofty goals in providing a voice in research to an underrepresented group and in analysing how disability is portrayed in society at large. However, several of the arguments presented in the context of cultural disabilities studies are incompatible with my lived experience.

### 3.3.4. The language of disability

As I explained previously, cultural disability studies focus strongly on analysing the societal discourse weaved around disability. Although I have highlighted the limitations and potential dangers that could arise if such theoretical discussions are taken too far, I agree with Mankoff et al. (2010) in that language shapes the way we think about disability, so it should be considered carefully. Hence, in this section I will touch on the person-first versus identity-first language and provide my position, among other issues related to the use of language to describe disability.

The American Psychological Association (APA) recommends the use of person-first language (i.e. person with a disability) and this has become the standard in the USA. However, several cultural disability authors prefer the use of identity-first language (i.e. disabled person, deaf person), and this has become the standard in the UK (Dunn & Andrews, 2015; Mankoff et al., 2010; Shakespeare, 2013). Both camps make strong arguments as to why one naming convention should be preferred over the other, and my aim here is not to contribute to the discussion of person-first versus identity-first language, but just to explain the rationale behind the use of language that the reader should expect throughout this thesis.

As much as possible, I will try to follow the use of person-first language (i.e. person with a disability, people with visual impairment). First, this is to align my language with the preferred language used in Australia, which is where I am writing this thesis from. Furthermore, I will avoid the use of euphemisms such as “differently abled”, “people of all abilities”, “disAbility”, “diffAble”, “special needs”, et cetera, as these are considered patronising (*Inclusive language*, n.d.). Second, I try to use person-first language because of the influence of Spanish, my first language, in the way I express myself. Particularly in Ecuador, my home country, the convention is to use person-first language.

I also feel the need to discuss the use of the words “impairment” and “disability”. As explained before, the strong social lens uses these words as a dichotomy and suggests that, while the impairment is innate to the individual, disability is created by society (Shakespeare, 2013). However, in Spanish both “impairment” and “disability” translate to the same word: “*discapacidad*”. I will try to be mindful of the distinction between disability and impairment when relevant, but once again, due to the influence of my first language, I might involuntarily interchange them.

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To conclude this section, I would like to touch on the word “crip” (short for cripple). I will not use this word. In fact, I feel strongly against it. The popularity of the word crip in academic literature has risen due to the development of Crip Theory by Robert McRuer (2006). This theory finds itself at the intersection of queer studies and disability studies, as both explore the relationship between the normal and the “abnormal”: straight/gay, abled/disabled (Löfgren-Mårtenson, 2013). As I explained in the previous section, this view fails to recognise the fact that disability is not neutral and almost always entails a limitation (Shakespeare, 2013). Leaving crip theory aside and focusing on the word itself: although some authors in favour of its use prefer it because of its “radical edge” and argue for its use in order to subvert expectations (Sandahl, 2003), given my lived experience of disability and the fact that English is my second language, I find it hard to see past the demeaning connotations of the word. Furthermore, and to my surprise, the word has more violent undertones, as it is the name of a gang from Southern California and is associated with street warfare (Bone, 2017). I believe we do need a more holistic view to understand disability; however, I am wary of radical activism, so I would prefer to distance myself from the word crip.

### 3.3.5. Passion and empowerment

Before describing the next theoretical lens used to conceptualise disability, I would like to explore concepts that are relevant for the field of HCI that have been brought forth by the cultural disability studies lens. First, I will discuss the four discourses of disability identified by Moser (2005), who studied how these four discourses—which she calls ordering—reflect in practice. Then I will explain how the discourse of passion correlates



with the rhetoric of empowerment developed by Rogers and Marsden (2013), and how these ideas have informed the development of future chapters of this thesis.

The reason why I have decided to describe Moser's ordering of disability is because her theoretical arguments are supported by empirical observations, and this aligns with my personal stance on how to approach disability. Moreover, although Moser's analysis started with a strong theoretical grounding, she concluded that disabled is not something one is, but something one becomes, and that one becomes disabled due to an interplay of different factors, not just due to societal constructs. This conclusion is similar to the critical-realist lens described by Shakespeare (2013), which I will explain in the next section.

According to Moser (2005), there are four ways in which disability is ordered. There is the order of the normal, disability as lack, the normative of fate, and the order of passion.

- **The order of the normal:** this ordering is based on the medical lens discussed earlier and argues that disability is a characteristic of the individual that needs to be corrected—normalised. This normalisation is enacted by moving agency away from the person with an impairment and into external factors i.e. policy, assistive technologies, et cetera.
- **Disability as lack:** based on empirical evidence, Moser states that disability may be understood as the lack of something. In the case, for example, of someone with aphasia—inability to understand or produce speech as a result of a brain injury, a person may be capable of complex thought but lacks the ability to communicate it.

- **The normative of fate:** is the recognition that most things in life—including disability—are outcomes of circumstances that are, for the most part, beyond our control. This order does not see disability as something “tragic” or “cruel”, nor as something that needs to be “fixed”, but rather as an inescapable dimension of life.
- **Passion:** finally, Moser argues that after accepting disability as fate, one may strive to regain agency by engaging in activities that produce passion: “neither mastery and control nor passive acceptance, but an experience of being immersed” (Moser, 2005, p. 682).

Although these four orderings of disability are distinct, Moser (2005) makes the point that the way disability is perceived is fluid and varies across these four orderings. Indeed, reflecting on my own lived experience, I can see my own use of glasses as an attempt to *normalise* my vision; however, upon removal of my left eye from its socket, no glasses will ever compensate the literal *lack* of my left eye. Furthermore, I accepted from an early age that my circumstances were different from those of others—I accepted my *fate* as someone with diminished visual acuity. That acceptance has led me to live a life where I actively and *passionately* enjoy subverting the expectations of what I can and cannot do.

Beyond my anecdotal experience, Rogers and Marsden (2013) have argued that in the field of technology interventions for people with disabilities and akin to the medical tradition, technology design has often followed a “third-person vein”, where the focus is on designing solutions based on what we as designers think people with disabilities need, framing technology as a means to compensate—normalise—for what is lacking. Although this approach has certainly led to the development of useful advancements in

technology for people with disabilities, Rogers and Marsden (2013) argue it is time we moved to the development of solutions that empower people with disabilities and support them in realising their passions. Rogers and Marsden (2013) argue that HCI is key to facilitating this change in paradigm, given its strong focus on working with people. They conclude that HCI researchers should design for “empowering people to engage with technology in innovative ways that stretch others’ imagination and tap into their wisdom and worldviews”. This is a call to recognise the skills developed by people with disabilities through their lived experiences while producing creative solutions that enable them to engage with technology in ways not possible before. As it will become clear in later chapters, these ideas have informed my own approach to solving the research questions posed in the first chapter of this thesis.

### 3.3.6. The critical-realist lens

I have explained how the medical and strong social lenses have focused on rehabilitation and cure, and barrier removal respectively; however, these lenses undervalue the lived experience of disability. On the other hand, I have explained how the cultural disability studies lens was created to recognise the importance of the lived experience of disability and its portrayal in society, but the extrapolation of some of the ideas proposed under this lens have the potential to be detrimental to the lives of people with disabilities. I believe—like Shakespeare (2013), that we need a lens that recognises the importance of the lived experience of disability while encouraging empirical enquiry, as opposed to following theoretical analyses whose practical implications for the lives of people with disabilities may be detrimental. I strongly support Shakespeare (2013) when he says: “I am unashamedly eclectic and pragmatic in my theoretical allegiances, finding a plurality of

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approaches beneficial in the analysis of disability” (p. 72). This is not to say that theory is irrelevant, but that the priority of the research approaches should focus on what is most beneficial for people with disabilities. I suspect that both Shakespeare and I concur in our preference for a plurality of approaches because, as disabled persons who have worked with other people with disabilities, we are aware that different people with the same impediments will follow different strategies to cope with their impediments, so a nuanced response is required.

The critical realist approach to science was first described by Bhaskar (1975), who argued that “things exist and act independently of our descriptions, but we can only know them under particular descriptions” (p. 250). In the context of disability, this implies that there is a biological component of disability that exists “and acts independently of our descriptions” but the implications of that biological component can only be known by the descriptions we make about it. These descriptions will inevitably be shaped by our societal context. This approach recognises the existence of impairments and their own experiential reality even if societal assumptions around these impairments change over time (Shakespeare, 2013).

Under a critical realist lens, Shakespeare (2013) conceptualises disability as an interaction. In his words:

*“Rather than getting fixated on defining disability as a deficit or a structural disadvantage or alternatively a product of cultural discourse, a holistic understanding is required. Put simply, the experience of a disabled person results from the relationship between factors intrinsic to the individual, and extrinsic factors arising from*

*the wider context in which she finds herself... People are disabled by society and<sup>4</sup> their bodies” (pp. 74-75).*

The factors to which Shakespeare refers may include: the biological element of the impairment, a person’s attitude towards it, their abilities and personality, the attitudes and reactions of others, and wider societal, cultural, and economic factors (Shakespeare, 2013). The conception of disability as an interplay is powerful in that it encourages research to move beyond discourse and focus on action while at the same time recognising the value of both the individual experience of disability and the importance of the social discourse around it.

As I described earlier, it might be tempting for researchers in the field of HCI to design technology interventions for people with disabilities following the medical lens, as it provides a set of functional requirements to “normalise” the functions of people with disabilities (Frauenberger, 2015; Mankoff et al., 2010). However, Shakespeare (2013) reminds us that under a critical realist perspective, we should strive to go further. In Shakespeare’s words: “enhancing [the] self-esteem and self-confidence [of people with disabilities] may sometimes transform their lives as much as providing better facilities or access to medical treatments” (p. 82). As digital games become more commonplace in society and their positive effects on the psychological wellbeing of individuals are better understood (Adachi & Willoughby, 2016; Ingram & Cangemi, 2019), research that seeks to make such games more accessible—like the research presented in this thesis—is not only justified, but desirable. The ultimate goal of this type of research would be to facilitate the integration of people with disabilities who desire to engage with mainstream

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<sup>4</sup> Original emphasis of the author

digital games without attracting any special—undesired—attention, without being singled-out because of their disability, and enabling them to mix with others without being ignored in social networks (van de Ven et al., 2005). Although this level of integration is still a long way away in the context of digital games, the research presented in this thesis is a step in that direction.

### 3.4. The critical-realist agenda for assistive technology

It is not enough to declare one's theoretical affiliations, it is necessary to articulate how these affiliations inform the design of the research. In the case of the medical, strong social, and cultural disabilities lenses, that is clearly determined: normalise, remove barriers, and focus on representation. In the section below, I reflect on what it means to be a critical-realist researcher in the field of HCI.

To help with this reflection, my thinking about how critical realism is present in my research is informed by the “critical realist agenda for assistive technology” described by Christopher Frauenberger (2015). This agenda proposes a series of characteristics that researchers should consider in order to ensure their research aligns with the critical realism lens. These characteristics are: ensuring a multi-faceted and interactional approach; methods; evaluation; ethics and morality; and knowledge. I will provide short definitions of these characteristics and explain how they apply to my own research.

**Multi-faceted and interactional:** as explained in the previous section, a critical realist researcher should consider disability as an interaction of several factors: from the biological to the attitudinal to the social. Hence, the role of technology interventions may be just as diverse, and the critical realist researcher must be mindful of the interaction of

their intervention with these factors. By conducting parts of this research in Australia, Ecuador, and online with a range of participants from several countries, this research benefits from a global perspective that gives this work unique insights from people from different cultural and backgrounds. Additionally, this research has included participation from both expert gamers with visual impairment and people who had never engaged with digital games. As a result, this work describes a rich range of attitudes regarding accessibility and digital games. Finally, the decision to not recruit sighted participants—to be explored further in the following section—emphasises the importance of recognising the value of the biological factor of impairment. All these decisions enable this work to present a multi-faceted and nuanced portrayal of the relationship between accessibility and digital games.

**Methods:** should support answering the following question: “how can we design technology that is multi-faceted and interactional?” In this thesis, I have chosen a combination of qualitative experiential interviews and laboratory-based evaluations to explore different aspects of the gaming experience of people with visual impairment and the effectiveness of echolocation to improve their ability to explore virtual worlds. This choice of methods highlights the importance of the lived experience of persons with disabilities. Furthermore, insights gained from this diversity of methods are integrated during each step of this research, contributing to the development of a multi-faceted solution. Additionally, the last study of this thesis uses participatory methods to ensure that the technology developed truly responds to the needs of people with visual impairments.

**Evaluation:** this refers to answering the question: what does it mean for technology to work for people with disabilities? In line with Shakespeare (2013), I have sought to

incorporate a critical realist approach by holding the view that the best way to find out what works for people with disabilities and conduct meaningful evaluations, is to ask them directly. Therefore, all evaluations conducted as part of this research have been done with people with visual impairments. Another important consideration for evaluation in a critical realist context is remembering that interventions in virtual worlds do not have to necessarily mimic interventions in the physical world. If, for example, an implementation of echolocation in virtual worlds created with off-the-shelf components works for people with visual impairment, asking how similar this implementation is to echolocation as it occurs on the physical world might be best answered by research guided by a medical lens. The focus of evaluation should be on finding what it means for something to work for people with disabilities, not on how an intervention compares to other.

**Ethics and morality:** all research conducted on human participants entails an inescapable ethical dimension. Moreover, research projects involving human subjects must adhere to the “National Statement in Ethical Conduct in Human Research<sup>5</sup>” in Australia, and at The University of Melbourne “human ethics approval is required for all research conducted with or about people<sup>6</sup>”. The ethical aspect of research is particularly relevant for the critical realist researcher, who must constantly reassess the ethical and moral considerations tied to the research project, as their understanding of interactional nature of the disability with the proposed technology intervention expands (Schön, 1984). This project is no exception, and although I received ethics clearance from the University

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<sup>5</sup><https://www.nhmrc.gov.au/about-us/publications/national-statement-ethical-conduct-human-research-2007-updated-2018>

<sup>6</sup> <https://staff.unimelb.edu.au/research/ethics-integrity/human-ethics>



of Melbourne Ethics Committee (Ethics ID 1851274 and 1749810), my ethics applications received several amendments as my understanding of the problem grew or as circumstances and potential risks for participants changed: I had to ensure that the ethics application I submitted reflected my understanding of the issues at hand and protected the best interest of participants, reflecting what Guillemin and Gillam (2004) call “ethics in practice” as a means to account for development that could not have been foreseen when developing the corresponding ethics application.

**Knowledge:** research should lead to an improved understanding of the phenomenon of disability, and this understanding should be “translated into a shared body of knowledge by the virtue of being re-used, re-interpreted and built upon” (Frauenberger, 2015, p. 93). I have taken a twofold approach to addressing this point: from the point of view of design, I have chosen to use already existing off-the-shelf components to conduct my experimental studies, in hopes that this will make it easier for others to build on top of the technologies I have used; from the point of view of ensuring the knowledge I have generated is available to be re-used and re-interpreted, I made the conscious decision from the beginning of my PhD to write a thesis with publication, whereby peer-reviewed papers become part of the final thesis. This will make it easier to disseminate the findings at different stages of progress of my PhD.

To summarise: I will align my research with the critical-realist agenda proposed by Frauenberger (2015): to ensure my research is *multi-faceted and interactional*, I will explore the social dimension of playing digital games as a person with visual impairment, with gamers and non-gamers with visual impairment who come from a variety of countries and cultures; my *methods* are a combination of laboratory-based evaluations with experiential interviews to explore different aspects of the problem I am studying;

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*evaluation* will be conducted only with people with visual impairment and it will focus on finding “what works best”; the *ethics* requirements of the project will be constantly assessed and updated to reflect changes in my understanding of disability and changes in potential risks for participants; and *knowledge* will be shared through the writing and publication of several academic articles during the length of the PhD, and through the use of freely available technology. This approach is not perfect, as I, for example, do not cover the economic and social factors of disability and their relationship with access to technology during my evaluations, but as Shakespeare (2013) argues, my project speaks to the need to have more empirical studies to understand a complex problem, in this case, that of ease of exploration of virtual worlds by people with visual impairment.

### 3.4.1. Critical realism and participant selection

There have been debates about what constitutes a valid sample size in an HCI study, with a median sample size of 12 at the *Conference of Human Factors in Computing Systems (CHI)*, one of the most prestigious in the field (Caine, 2016). Despite this median sample size, Caine (2016) acknowledges that the nature of the project and the constraints associated with it affect the sample size attained. In my case, the biggest constraint I have self-imposed on my study, as a critical realist researcher, is the recruitment of people with visual impairment. I believe, like Shakespeare (2013) and Frauenberger (2015), that the best way to find out what works for people with disabilities is to ask them directly. Moreover, I concur with the argument that employing sighted blindfolded participants is not a valid substitute for people with visual impairment, as this approach does not recreate the experience of disability, but rather the initial shock associated with the loss of a sense (Silverman, 2015; Silverman et al., 2015). Furthermore, echolocation studies involving

sighted and blind individuals have consistently found that blind participants outperform their sighted counterparts (Kolarik et al., 2014; Kupers & Ptito, 2014; Rosenblum et al., 2000). For all these reasons, I'm committed to working with people with visual impairment to conduct the user studies outlined in the following section.

### 3.5. Methodological approach and study structure

This thesis investigates the problem of acquisition of spatial information in virtual worlds by people with visual impairment by using echolocation. My pragmatist worldview has enabled me to choose the methods that would best help answer the research question(s) beyond answering to the postpositivist/constructivist dichotomy. Moreover, the critical realist lens that has informed this research has encouraged the use of methods that support a holistic understanding of the relationship between disability and technology and recognise the importance of both the lived experience of people with disabilities and the need for empirical evidence. To investigate the problem described above, I have conducted three user studies, where each user study addresses one or two of the research questions posed in chapter one. To recapitulate, the main research question I explore in this thesis is: *how can echolocation be designed as a means for people with visual impairment to acquire spatial knowledge of a virtual space?* To address this question, the following sub-questions have been formulated:

- **RQ1:** How do people with visual impairment currently engage with virtual spaces (digital games and augmented/virtual reality experiences)?
- **RQ2:** How can echolocation be implemented in virtual worlds so that it supports acquisition of spatial knowledge?

- **RQ3:** What features of virtual space can be revealed through echolocation?
- **RQ4:** How do the features revealed through echolocation support acquisition of spatial knowledge in virtual space?
- **RQ5:** How can a co-creation process informs the design and implementation of echolocation in virtual spaces?

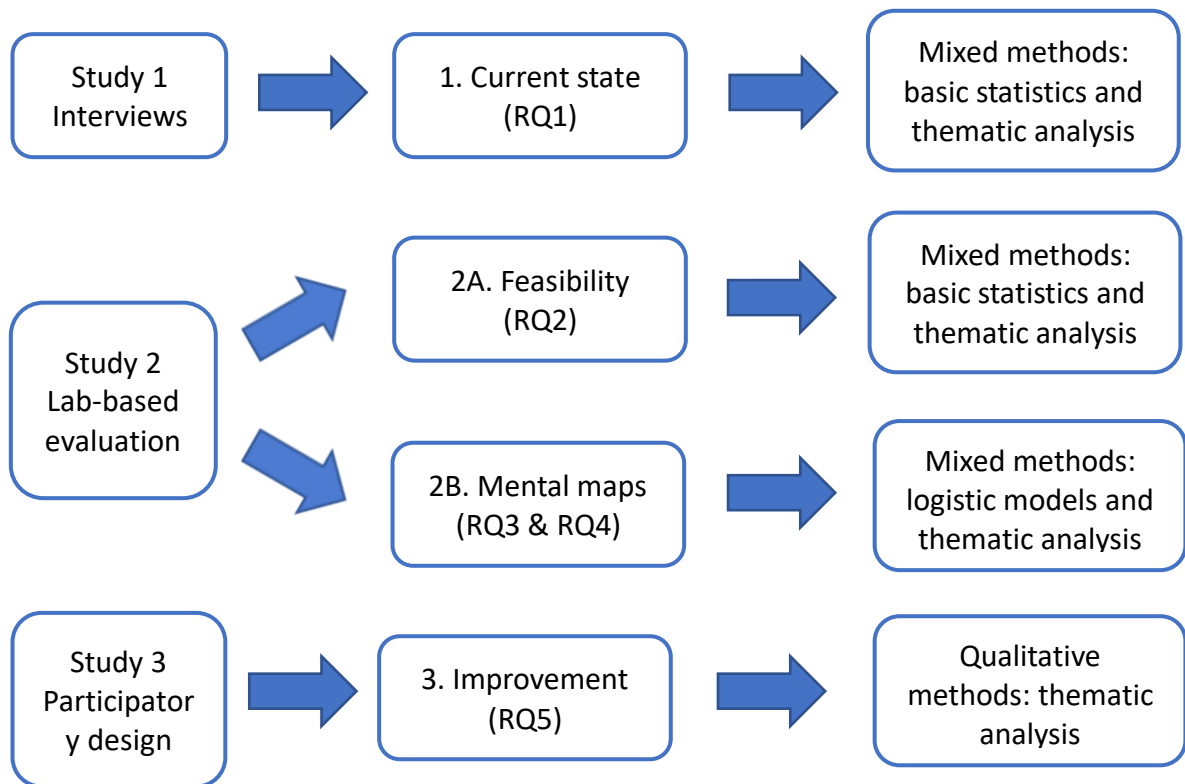


Figure 3. Studies conducted and methods used

The research questions described above will be answered through three different user studies that are presented in this thesis in chapters four through eight, comprising sections II and III of this work. Figure 3 shows the relation between each study, the data collection method used (interviews, lab-based evaluations or participatory design), the general goal of the study with the research question it addresses, the methods used

(qualitative, quantitative or mixed) and the tools used for data analysis. The following sections provide an overview of these three studies.

### 3.5.1. Study 1

Study 1 reflects the critical realist nature of this research by providing a holistic view of the habits, opinions and concerns of gamers with visual impairment from different parts of the world. Study one also presents a reflection on the elements that, according to expert gamers with visual impairment, enable access to digital games in the first place. Furthermore, by studying the relationships between digital games and people with visual impairment, this study speaks to the interactional nature of critical realism (Frauenberger, 2015; Shakespeare, 2013).

Study 1 follows a mixed-methods approach and an explanatory sequential design (Creswell & Plano Clark, 2011) where quantitative data are first collected and analysed, then qualitative data are collected to provide richer insights into the initial quantitative findings. In it, empirical data on the habits of gamers with visual impairment—the types of games they play, for how long they play, et cetera—are collected via an online survey. These survey data are analysed with simple descriptive statistics. Afterwards, this study explores the experiences of a group of gamers with visual impairment via in-depth interviews. The interviews are analysed using thematic analysis, as described by Braun and Clarke (2006) and Braun and Clarke (2012). Study 1 provides a snapshot of how people with visual impairment engage with virtual spaces and answers **RQ1**. The results from study 1 are synthesised in two peer-reviewed papers and presented in chapters four and five.

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### 3.5.2. Study 2

Study 2 introduces the use of off-the-shelf tools to create echolocation-enabled virtual environments that support the acquisition of spatial information. This study is divided in studies 2A and 2B. Following the critical realist approach described in this chapter, this study addresses what it means for technology to work for people with disabilities. Furthermore, the design decisions taken in study two—particularly in study 2B—are informed by the findings from study one and 2A. This approach effectively supports my critical realist perspective and the empowerment approach to HCI promoted by Rogers and Marsden (2013), where the unique skills that people with disabilities develop through their lived experience are leveraged to design technologies that allow enable them to engage more seamlessly with technology and foster passion.

#### **Study 2A**

Study 2A addresses **RQ2**. It presents an exploratory laboratory-based evaluation to establish how to implement an echolocation-enabled virtual environment by using off-the-shelf components. This study uses a range of mixed methods and an explanatory sequential design (Creswell & Plano Clark, 2011). In this study, quantitative data related to participant performance are collected and analysed with simple descriptive statistics, and rich qualitative data about participants' subjective experience are collected via semi-structured interviews. The findings from study 2A were presented in a peer-review paper and appear on chapter six of this thesis.

#### **Study 2B**

Study 2B addresses **RQ3** and **RQ4**. This study builds upon the findings from study 2A to improve on the initial design of the echolocation-enabled virtual environment and focuses on using echolocation to learn spatial information. More specifically, this study explores whether echolocation can be used to detect the following features: the “material” a virtual room is made of, the relative size of different virtual rooms, the presence of 90-degree left and right turns, the presence of door openings, and the presence of obstacles. Afterwards, this study explores whether this knowledge can then be used and combined to create a mental map of virtual space. This study uses a mix of both quantitative and qualitative methods in an explanatory sequential design pattern (Creswell & Plano Clark, 2011). Quantitative data related to participants performance when detecting each of the features described earlier are automatically collected and used to create a statistical regression model. This model allows me to answer **RQ3** with a statistically significant level of confidence.

Participants subjective perception about their ability to detect spatial features of virtual space and their ability to create a mental map of the space they explored are captured via interviews and the use of a reconstruction task. In this task participants have to recreate the space that they explored using modelling clay. The interviews and the reconstruction task address **RQ4**. Data from the interviews are analysed using thematic analysis, the findings were presented in a peer-reviewed paper and appear on chapter seven of this thesis. As of the time of writing this thesis, the paper is currently under peer review.

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### 3.5.3. Study 3

The importance that a critical realist lens places on the lived experience of people with disabilities to build a holistic understanding of the relationship between disability and technology means that participatory approaches are encouraged (Frauenberger, 2015). To conclude this thesis emphasising the importance of learning from the experiences of people with disabilities to design empowering technologies, this thesis concludes with a participatory design exercise that seeks to describe how to design an enjoyable echolocation-in-virtual-worlds experience, informed by expert echolocators.

Study 3 addresses **RQ5** via a focus group session with three expert echolocators followed with two prototyping and evaluation cycles. The participants had experienced the echolocation-enabled virtual environment built for study 2B, so they have had experience with echolocation in virtual worlds before the focus group session. All data captured for Study 3 are qualitative and are analysed using thematic analysis. This analysis led to the design of seven design recommendations to successfully implement echolocation in virtual worlds. As of the time of writing this thesis, the findings from this study have been condensed into a paper. This paper has not yet been submitted for peer review, as it references the paper presented in chapter seven, which is under peer review at the time of finalising this thesis.

As I have indicated before, the use of mixed methods has been criticised because many mixed methods writers either: are not clear about their worldview, or tend to lean more towards a postpositivist worldview and understate the importance of subjective views (Creswell & Plano Clark, 2011; Denzin & Lincoln, 2011). It is my hope that the description of pragmatism and critical realist studies that I have provided, together with the plan I have outlined in this section, be sufficient to dispel those criticisms. As I have



said before, the choice of methods has been based upon what would work best to answer the research question at hand, instead of focusing on sticking with either quantitative or qualitative methods. This is necessary to obtain an in-depth understanding of the interactional nature of disability proposed by critical realism. Furthermore, HCI is the perfect field to bring diverse theoretical and methodological perspectives. Indeed, the field is seen as “a discipline that has often proceeded with something of a mix-and-match approach, liberally and creatively borrowing ideas and elements from different places” (Dourish, 2014, p. 2). Hence the suitability of my approach to research.

### **3.6. Summary**

In this chapter, I have described different worldviews and explained why I hold a pragmatist worldview. I have then described the different lenses that have emerged to understand disability—the medical lens with its focus on normalisation, the strong social lens with its focus on barrier removal, the cultural disability studies lens with its focus on discourse, and the critical-realist lens, which conceptualises disability as interactional, and I have argued in favour of the latter. Then I proceeded to describe the critical realist research agenda proposed by Frauenberger (2015) and described how my research aligns with it. I dedicated a few paragraphs to discussing the importance of language when talking about disability, articulated my choice of person-first over identify-first language, and conceptualised passion and empowerment in the context of designing assistive technology. Finally, I concluded by presenting an outline of the three studies to be performed to answer my proposed research questions and the methods used in each study.

More broadly, the end of this chapter indicates the end of the first section of this thesis. This section has provided an overall view to this entire thesis, discussed the works

### Chapter 3: Methodological Framework

of previous authors, and outlined the theoretical foundations of this work. Future chapters move towards the application and implementation of the theoretical foundations outlined in this chapter, starting with the second section of this thesis, which focuses on exploring the interactional nature of disability by voicing the habits, opinions and concerns of gamers with visual impairment, and identifying the game elements that, according to expert gamers with visual impairment, make games accessible.

Section II:

People



# **Chapter 4: Understanding Gamers with Visual Impairment**

## **4.1. Introduction**

The first section of this thesis provided the theoretical foundations for this work. Chapter one provided an introduction to this work, chapter two presented a survey of relevant literature, and chapter three outlined the importance of constructing a vision of disability that is holistic, multi-layered and interactional. Moreover, in chapter three I argued that, to provide such a view, it is necessary to recognise the importance of the lived experience of persons with disability and their unique skillsets (Rogers & Marsden, 2013; Shakespeare, 2013). The aim of Section II is to help construct a holistic vision of how people with visual impairment engage with virtual spaces. To achieve this goal, section two presents the results of Study 1. Particularly, chapter four presents a set of insights into the habits, opinions and concerns of a group of expert gamers with visual impairment, while chapter five describes the elements that, according to expert gamers with visual impairments, enable access to digital games. The expert gamers' experiences were collected through the use of a survey and a series of interviews. Exploring these issues is—according to a critical realist approach—a crucial first step in designing a new metaphor to improve how people with visual impairment engage with digital games.

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The survey and subsequent interviews with gamers with visual impairment used in study 1 that are summarised in this chapter revealed the gamers' gameplay habits, their opinions regarding the importance of digital games in their lives, and their concerns around new and emerging technologies. The two chapters that comprise section II contain a publication each. As I have discussed in chapter three, the aim of producing a thesis with publication supports a critical realist view values sharing information so that others can build on and benefit from it.

This chapter presents a conference paper entitled “Playing Blind: Revealing the World of Gamers with Visual Impairment”. The paper was rigorously reviewed by three anonymous<sup>7</sup> reviewers and a meta-reviewer and was accepted for publication in the *Proceedings of the 2019 CHI Conference in Human Factors in Computing Systems*. The paper is added to this chapter “as is” with no modifications. References included in the paper are presented as part of it instead of in the References section at the end of the thesis. The paper presented in this chapter provides a valuable resource for researchers and game developers, as it highlights a series of issues that are relevant for gamers with visual impairment.

### 4.2. How this paper contributes to the thesis

This paper presents parts of the findings from Study 1 and focuses on exploring the gaming experience of gamers with visual impairment from the gamers' point of view based on empirical data—as opposed to presenting the researcher's theoretical

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<sup>7</sup> I will not use the term “blind reviewers”, as I find it inaccurate

perspective on the topic—and directly addresses **RQ1**: how do people with visual impairment currently engage with virtual spaces? This paper demonstrates that there is an active community of gamers with visual impairments who engage with games in similar ways as sighted gamers do, despite having to face particular challenges.

More importantly, this paper addresses the need to conduct research that is interactional, according to a critical realist lens (Frauenberger, 2015; Shakespeare, 2013). That is, this research recognises that there are a series of factors that affect the experience of people with visual impairment who engage with digital games. By working together with expert gamers with visual impairment, this research uncovers some of these factors. Furthermore, this paper embraces the concept of empowerment described in chapter three, and argues that although people with visual impairment see new and emerging technologies such as augmented and virtual reality (AR/VR) as a threat, these technologies provide an opportunity for HCI research to design empowering experiences that foster passion and recognise the unique skillsets of people with visual impairment (Moser, 2005; Rogers & Marsden, 2013).

### **4.3. Data collection and analysis methods**

The study presented in this paper follows an explanatory sequential design (Creswell & Plano Clark, 2011, pp. 53-106), where a quantitative data collection and analysis phase is followed by a qualitative data collection and analysis phase. The role of the qualitative phase is to follow up from the first phase of the study to provide depth, richness, and a way to interpret the initial quantitative results. The first stage of the study consisted of an online survey posted in a site that hosts a community of gamers with visual impairment. Quantitative analysis tools used during the first stage of this study were descriptive

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statistics, such as frequencies and averages. The goal of the survey was two-fold: first, it aimed to explore the habits of gamers with visual impairments—the types of games they play, for how long they play, with whom they play, et cetera. Second, it worked as a tool to invite gamers with visual impairment to participate in the second—qualitative—stage of the study.

The second stage of this study consisted of in-depth online interviews with participants recruited through the initial survey. This qualitative stage provided a richer view on the habits, opinions and concerns of gamers with visual impairment. Data collected through interviews were analysed using thematic analysis, as described by Braun and Clarke (2006) and Braun and Clarke (2012). These interviews revealed several aspects of the relationship between gamers with visual impairment and the games they engage with. Particularly, the results focused on: the reasons why gamers with visual impairment engage with digital games; the importance of story and narrative in games; the tension of having games that are accessible and challenging at the same time; the social trajectories built around gameplay; gamers' desire for in-game self-representation that moves away from pre-conceived stereotypes; gamers' opinions about accessibility in mainstream gaming platforms, such as *Xbox* or *Steam*; and gamers' encounters with virtual and augmented reality experiences.

### 4.4. The paper

A PDF file of the paper can be found at: <http://go.unimelb.edu.au/kd9j>.



# Playing Blind: Revealing the World of Gamers with Visual Impairment

**Ronny Andrade**

The University of Melbourne  
Melbourne, VIC, Australia  
andrader@unimelb.edu.au

**Melissa J. Rogerson**

The University of Melbourne  
Melbourne, VIC, Australia  
melissa.rogerson@unimelb.edu.au

**Jenny Waycott**

The University of Melbourne  
Melbourne, VIC, Australia  
jwaycott@unimelb.edu.au

**Steven Baker**

The University of Melbourne  
Melbourne, VIC, Australia  
steven.baker@unimelb.edu.au

**Frank Vetere**

The University of Melbourne  
Melbourne, VIC, Australia  
f.vetere@unimelb.edu.au

## ABSTRACT

Previous research on games for people with visual impairment (PVI) has focused on co-designing or evaluating specific games - mostly under controlled conditions. In this research, we follow a game-agnostic, "in-the-wild" approach, investigating the habits, opinions and concerns of PVI regarding digital games. To explore these issues, we conducted an online survey and follow-up interviews with gamers with VI (GVI). Dominant themes from our analysis include the particular appeal of digital games to GVI, the importance of social trajectories and histories of gameplay, the need to balance complexity and accessibility in both games targeted to PVI and mainstream games, opinions about the state of the gaming industry, and accessibility concerns around new and emerging technologies such as VR and AR. Our study gives voice to an underrepresented group in the gaming community. Understanding the practices, experiences and motivations of GVI provides a valuable foundation for informing development of more inclusive games.

## CCS CONCEPTS

• **Social and professional topics** → **People with disabilities**; • **Applied computing** → *Computer games*;

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## KEYWORDS

visual impairment, digital games, audiogames, empowerment

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## 1 INTRODUCTION

When designing technology for people with visual impairment (PVI), there has been a strong focus on the design of tools for navigation and wayfinding [2, 44, 60, 63, 76, 82, 85], for mobility training [122], and tools for creating, communicating and rendering graphical information [3, 17, 75], with less attention being placed on leisure activities such as creating art [52], travel [104], dating [65], participating in sport or physical activity [31, 56, 73], making music [30], and playing games.

Games in general, and digital games in particular, rely heavily on visual stimuli to present information to players. Indeed, digital games are commonly referred to as videogames, a name which emphasises their visual, "video" content. This reliance on visual information excludes PVI, as games demand sensory capabilities that exceed those of PVI [29, 118]. With digital games becoming an ubiquitous cultural phenomenon [20, 42], exclusion of PVI needs to be addressed.

Many digital games have been designed to address exclusion of PVI. Some may include a graphical interface, and can therefore be categorised as videogames. Some games have focused on assisting PVI to navigate physical locations by reproducing these locations in a virtual environment, obtaining improved orientation and mobility outcomes [32, 94, 95]. Others have focused on the use of videogames for educational purposes, designing interesting interaction mechanisms such as compass, radar, and musical metaphors [66, 103]. Others

have argued for the need of equitably accessible games, and designed videogames for PVI for hedonic purposes [100].

Apart from research-driven initiatives, gamers with visual impairment (GVI) have responded to the challenge of interacting with visually rich videogames by engaging with Multi-User Dungeons (MUDs), audiogames, and mainstream games to an extent. MUDs are text-based adventures and its origin dates back to the 70s [12]. By being text-based, MUDs are accessible to existing accessibility software. Audiogames are a type of digital game that includes an entirely auditory interface and may or may not include a graphical interface [45, 66]. The engagement of GVI with mainstream games depends on their remaining sensory capabilities.

Unlike previous studies, we have not designed a game especially for PVI. Rather, we present findings from a study that investigated the current experiences and preferences of GVI. We have followed a game-agnostic, "in the wild" approach that privileges the views of GVI. In doing so, we aim to understand the habits, opinions and concerns of GVI in regard to videogames. By giving voice to this under-represented group in the videogames literature, we seek to move towards an approach that empowers PVI and encourage their engagement with fun and inclusive gaming experiences [91].

## 2 RELATED LITERATURE

This study is concerned primarily with the habits and practices of GVI. Our work is informed by literature that considers broader issues of VI as well as by our understanding of games and more specifically, of audiogames and of other assistive technologies that have been deployed for PVI<sup>1</sup> both within and outside game settings. It reflects our belief that research into VI should focus not only on the instrumental supports and aids that PVI require but also on the "beauty" and the "wonder" of play purely for play's sake [122].

### HCI and people with visual impairment

There is a significant body of research that considers the specific difficulties experienced by PVI in using social media and crowdsourcing tools [105, 106] as well as issues related to employment and participation. PVI experience higher rates of unemployment and of underemployment than are found in the general population [53, 83, 107]. To date, much of this research has been focused on everyday participation, including key workplace issues such as accessibility and the education of sighted colleagues [109]. Dobransky and Hargittai [36] have explored internet adoption by people with disabilities in the US and argue that technology has a tremendous potential to include these individuals in an inaccessible

society. With the focus of accessibility research on workplace accessibility, PVI may feel excluded from creative and leisure activities [118].

There has been little work done in HCI to explore VI players' own practices and experience, although there are isolated examples of participatory design work with VI participants in HCI [52] as well as other work which examines workplace practices [21]. Harris [57] suggests that while people with disabilities are initially excited by new technology, many devices end up unused and forgotten. Similarly, Macdonald and Clayton [74], and Moser [79] argue that digital technologies seem to construct new disabling barriers. Rather than proposing new technologies, our research examines how PVI choose to engage with games as a leisure activity, and what accommodations they use and require.

### Games for PVI

There is a growing body of research into making gaming accessible for PVI [6–8, 14, 59, 108, 112, 118], allowing them to "experience some of the more advanced types of computer game technology and enjoyment that sighted gamers have taken for granted for many years" [10]. Like research into real-world navigation tools, responses to this have considered the accessibility of virtual environments [69, 113] as well as wayfinding [19] and sensory substitution [11, 77]. For example, some games have focused on assisting PVI to navigate physical locations by reproducing these locations in a virtual environment, obtaining improved orientation and mobility outcomes [34, 94, 95]. Some videogames have been designed for use in formal educational settings, utilising interesting interaction mechanisms which have been replicated in audiogames, such as compass, radar, and musical metaphors [66, 103]. Other researchers have argued for the need for equitably accessible games, and designed videogames for PVI for hedonic purposes [100].

Games specifically designed for players with VI include memory games [88], action games including first-person shooters [54, 66], platformers and racing games [66], boardgames [55], exergames [89], games with tactile interfaces [97], music games [66] including *Blind Hero* [117], interactive text-based games and MUDs [66], directional games [66], and games based on exploring 3D virtual worlds [47, 103], including *Terraformers* [111], *Swamp* [64], *Shades of Doom* [46, 115], and others. Games are also used instrumentally, for example to improve accessibility of the World Wide Web [108], as teaching aids [66, 93, 120], or to specifically address issues of game level creation [10].

Common to this research—which may include participatory designs with VI players—is a focus on what studios or designers can do to improve the experience of gaming with a VI; a primarily deficit-driven approach. Accessibility is *designed into games* and is *presented* to VI players. It has been

<sup>1</sup>Although we consider it to be insensitive to use an acronym to refer to a group of people, we have used PVI and GVI to refer to people/gamers with visual impairment to improve clarity of expression in this article.

suggested that this may be seen as normalising the discourse of disability by presenting PVI as dependent on technology [78].

Whilst deficit-driven approaches have led to valuable innovation to improve quality of life for PVI, recent work has called for a more positive approach which recognises the skills, competencies and knowledge of PVI [27, 119]. Gerling et al. point to the need to involve players with disabilities in development of both entertainment and education-oriented games, and provide recommendations for working with these players [50]. Sighted individuals wearing blindfolds are not a suitable proxy for participants living with VI [98, 100]. Inaccessible games, it is suggested, may be due more to oversight or omission than to a conscious design decision [58]. Audiences with a need for "multisensory types of feedback" are recognised as a "flagship context" for games user research [37].

It is perhaps ironic that more attention has been paid to obscuring in-game information for all players than to techniques for revealing information to PVI. For example the "Fog of War" technique, whereby the game intentionally occludes or reveals terrain information to the player based on their location or line of sight [18, 84] is a popular mechanism to reflect the "limitations of game characters' ability to perceive and monitor the world around them" [72]. In contrast, gamers with VI are already restricted in their ability to perceive objects and events and require mechanisms that reveal features that are obscured to them. A notable approach to inclusion of PVI –although not in the digital game space– is the work of the Meeple Like Us project [59], which provides an accessibility analysis for popular boardgames across eight factors which include visual accessibility. Boardgames provide not only visual but also tactile, "sensuous" appeal [92] and are an increasingly popular leisure activity.

### Audiogames

Audiogames [66, 90] are a specific form of digital game developed for PVI, featuring "complete auditory interfaces, so that they can be played without the use of graphics" [45]. These games use auditory cues such as speech, auditory icons (representational natural sounds e.g. the sound of a car crash or of a bleating sheep), and earcons (artificial sounds e.g. beeps, musical tones or sound patterns) to convey information to players [16, 35, 48]. There is no consistent set of earcons that is used across different games [113]; players must learn a new set of arbitrary sounds for each game that they play [45]. Audio mappings with greater articulatory directness [61] may be easier to learn than those which are purely symbolic [48]. In other words, the more a sound is like the sounds experienced in a comparable situation in the real world, the easier it is to learn and remember. Accordingly, a game or setting with a large number of earcons creates additional

cognitive load on players' memories [16]. Unlike a visual scene, sound is temporary rather than persistent; it must be repeated if it is to remain salient [66]. Excessive amounts of audio content may create overload, thereby complicating, rather than simplifying, gameplay [68]. Yet a lack of descriptive audio information was identified by one study as "the biggest deal-breaker for our blind respondents" [47].

Kirke [66] summarises the different types of audiogames, which are indexed at the website [www.audiogames.net](http://www.audiogames.net). Common interaction mechanisms in these games include verbal information, where players are provided with oral instructions on what to do; time-based mechanisms, where earcons indicate when to perform an action; and constrained navigation, where the player's character is limited to moving on a coordinate-based grid-like system [51].

Audiogames have been criticised for failing to offer the full range of gameplay experiences. In a call for positive design [119], Smith and Nayar compare blind-accessible videogames to a wheelchair ramp-enabled library that is filled only with digests of the original books, suggesting that "accessibility alone is not enough" and arguing for what they term equivalent accessibility –allowing people with disabilities to experience the world as others do, "with a similar sense of control (intention) and efficiency as sighted players can" [100]. They identify complexity as a critical element of gameplay that is poorly served by existing approaches to accessibility.

Binaural 3D sound may be used in games to provide directional cues for players [66]. This technique embeds directionality into sound recordings through the use of two high-fidelity microphones which are typically embedded in a dummy head, to emulate "the physical effects of the diffraction of sound waves by the human torso, shoulders, head and outer ears" [23]. Thus, binaural 3D sound allows "simulation of three-dimensional sound of the real source" [67].

More recently, echolocation has been proposed as a navigational tool in virtual environments [4]. Research over the past seventy years has shown that echolocation –using self-emitted noises such as mouth-clicks as well as the ambient sounds generated by a person's cane or shoes– is an effective tool for human navigation [96]. The prospect of supporting echolocation in virtual environments promises an additional tool for PVI, who already use a range of strategies in negotiating in-game virtual environments [4, 103].

### 3 AIMS AND CONTRIBUTIONS

Previous literature has generally explored games for PVI on a game-by-game basis, with the exception of Kirke [66], who provides a comprehensive list of the most common audiogames played by GVI. In this paper, we set out to explore the habits, opinions and concerns of GVI through a game-agnostic, "in the wild" methodology. We aim to understand the lived experience and practices of GVI in their interactions



with games and play. This research redirects the dialogue of disability surrounding GVI, moving away from an approach of compassion, where design is driven by a perceived deficit. Instead, we orient this research towards a positive, empowering approach, where we make explicit the needs and concerns expressed by GVI [27, 119]. This approach will inform the development of more accessible games through an understanding of the trajectories and practices of GVI.

#### 4 METHODS

Our research comprised an online survey and semi-structured interviews. The participants were PVI who are part of an online audiogame community. The study was approved by the University of Melbourne Ethics Committee (Ethics ID 1851274).

##### Online Survey

The survey aimed to understand respondents' existing gaming habits, their perception of interaction patterns in their favourite games, and their views on emerging gaming technology, such as VR and AR. The survey was advertised on the website [forum.audiogames.net](http://forum.audiogames.net), as the site specialises in audiogames and attracts GVI and game developers.

As someone with a visual impairment, the first author strived to establish a bona-fide relationship with members of the forum by providing answers to technology-related questions. This positioned him as both an insider within the PVI community [15] and an expert in the subject matter, developing credibility within the community for him and, by extension, for the research project.

The survey consisted of 24 questions. A copy of the survey is included in the supplementary material for this paper. The survey contained a series of single-choice, multiple-choice and open-ended questions. Some of the questions regarding participants' gaming habits were adapted from larger surveys by *The Entertainment Software Association* [42] and *Digital Australia* [20]. The survey was built using Google Forms and was tested for accessibility using Firefox 60.0 and the screen reader NVDA version 2018.1. Because PVI may experience difficulties filling in online surveys even when these are accessibility compliant [70, 71], we decided not to make questions mandatory. The survey was piloted with the University of Melbourne Web Accessibility lead, who has extensive experience working with people with disabilities. The survey was available for four weeks and was advertised on the forum on two separate occasions.

##### Interviews

At the conclusion of the survey, respondents were invited to volunteer for a semi-structured interview. Six people engaged in the interview, which was conducted in English. The

interviews aimed to get in-depth knowledge about interviewees' experiences and perceptions of gaming. The interviews explored interviewees' relationship with digital games, their thoughts on accessibility and games, and the factors that keep them engaged with games. Space was also allocated to allow interviewees to discuss any other topics they felt were important. The interviews were conducted via a medium that was preferred by the interviewees, allowing them to engage in a space where they felt most comfortable. Five interviewees preferred the video-conferencing software Skype and one preferred the audio-conferencing software TeamTalk. However, cameras were not enabled in any interview. While the interviews were scheduled to last around 20 minutes, participants were happy to go over the pre-established time to share their views. We obtained 186 minutes of interview recording in total.

##### Participants

Participation in both the online survey and the follow-up interview was voluntary; there was no compensation for participation. We received seventeen valid responses to the online survey and were able to contact six out of eight interested participants to take part in the follow-up interview. Participants were 18 years of age or more, spoke English as a first or second language, and had a self-reported degree of visual impairment that could not be corrected with glasses, including low visual acuity (mostly colour perception), loss of central vision, loss of peripheral vision, blindness (some light perception) or full blindness (no light perception). Table 1 shows demographic information of all our participants. Participants 1 through 11 participated in the survey only, and participants 12 through 17 participated in both the survey and the follow-up interview.

As shown in Table 1, participants came from North and South America, Europe, Asia and the Middle East. Only one of our participants was aged between 36 and 45 years while the other sixteen participants' ages fell between the range of 18 to 35 years. Twelve participants were male, four were female and one preferred not to disclose their gender. Ten of the seventeen participants declared the state of their vision as blind with light perception, four are blind with no light perception, and three self-identified as having low visual acuity, relying mostly on colour perception. In order to protect participants' privacy, they are referred to by pseudonyms.

##### Data Analysis

We analysed the multiple-choice answers from the survey by tabulating responses to individual questions. These results are presented in the section *Quantitative data from the online survey*.

**Table 1: Demographic information of participants. All participants completed the survey. Participants 12-17 continued to the semi-structured interview**

| N  | Age range | Name    | Gender            | Country              | Impairment (and onset)                                                          |
|----|-----------|---------|-------------------|----------------------|---------------------------------------------------------------------------------|
| 1  | 26 to 35  | P1      | Male              | No answer            | Low visual acuity. Colour perception.                                           |
| 2  | 36 to 45  | P2      | Male              | No answer            | Blind, light perception                                                         |
| 3  | 18 to 25  | P3      | Female            | Slovenia             | Blind, light perception                                                         |
| 4  | 18 to 25  | P4      | Male              | United Kingdom       | Blind, light perception                                                         |
| 5  | 18 to 25  | P5      | Male              | Turkey               | Blind, no light perception                                                      |
| 6  | 18 to 25  | P6      | Male              | United Arab Emirates | Low visual acuity. Colour perception.                                           |
| 7  | 18 to 25  | P7      | Female            | USA                  | Blind, light perception                                                         |
| 8  | 26 to 35  | P8      | Female            | No answer            | Blind, light perception                                                         |
| 9  | 18 to 25  | P9      | Male              | USA                  | Blind, light perception                                                         |
| 10 | 18 to 25  | P10     | Male              | USA                  | Blind, light perception                                                         |
| 11 | 18 to 25  | P11     | Male              | USA                  | Blind, light perception                                                         |
| 12 | 18 to 25  | Juan    | Male              | Canada               | Blind, no light perception (from birth)                                         |
| 13 | 18 to 25  | Marcela | Female            | Philippines          | Blind, light perception (early childhood)                                       |
| 14 | 26 to 35  | Alberto | Male              | Brazil               | Blind, no light perception (early childhood)                                    |
| 15 | 26 to 35  | CJ      | Prefer not to say | USA                  | Blind, no light perception (10 years old)                                       |
| 16 | 18 to 25  | Carlos  | Male              | Austria              | Blind, light perception (from birth)                                            |
| 17 | 26 to 35  | Jose    | Male              | USA                  | Low visual acuity. Colour perception.<br>Loss of peripheral vision (from birth) |

Extended answers from the open-ended questions in the survey and the follow-up interviews were analysed separately with the aid of the software NVivo 11, using thematic analysis and the step-by-step method proposed by Braun and Clarke [22]. Following Braun and Clarke, our first step was to transcribe, read and re-read our interviews [22]. We then followed an inductive approach, whereby codes were driven by the content of the data. Once the data had been coded, we proceeded to search for and identify trends or themes among the codes. These initial themes were then revised, formally defined and given a name. The first author coded all the interviews while two other researchers coded specific interviews in an attempt to ensure consistency and identify all relevant themes. While the individual themes identified by each researcher were worded differently, they encompassed similar ideas, with minor differences in emphasis based upon the framework of expertise of each researcher [9].

## 5 FINDINGS

The results from the online survey offered a snapshot of demographic information of GVI, frequency and duration of gameplay, preferred gaming device, and preferred types and genres of games. Moreover, responses to the open-ended questions in the survey showed some of the reasons why GVI engage with videogames, and their concerns regarding new gaming technologies, such as AR and VR. The follow-up interviews provided rich insights into the habits, opinions

and concerns of GVI. The themes derived from our analysis included: engagement with games and narratives, tensions of building games that are complex but accessible and appealing to the mainstream, the importance of social trajectories for gameplay, ideas around self-representation in digital games, opinions about accessibility in mainstream digital games, and concerns surrounding emerging technologies, such as AR and VR.

### Quantitative data from the online survey

Summary survey results are presented in Table 2. The results in this table correspond to questions that had single choice answers. The relatively high no answer rate to the first two questions may be explained by our decision not to enforce mandatory answering of all questions.

Table 2 shows that more than half of our respondents played videogames at least every other day. Duration of play was mostly more than two hours at a time. The table shows that while six respondents mostly played with others, the remaining respondents said they mostly played on their own. Most respondents reported to use the free and open-source screen-reader NVDA for Windows while playing.

Our respondents played games on computer (16), mobile phone (14), dedicated console (7), and handheld console (2). When asked about the genre of game they played, participants responded: role-playing games (RPGs) (15), platformers (10), fighting games (10), strategy games (10), shooters (9),

**Table 2: Responses to single-answer questions from the online survey**

| Question                                                      | Answer                   | Count |
|---------------------------------------------------------------|--------------------------|-------|
| How often do you play videogames?                             | Every day                | 6     |
|                                                               | Every other day          | 6     |
|                                                               | Once a fortnight         | 1     |
|                                                               | [no answer]              | 4     |
| When you play, for how long do you usually do it?             | 30 minutes to 1 hour     | 1     |
|                                                               | 1 to 2 hours             | 4     |
|                                                               | 2 to 3 hours             | 2     |
|                                                               | 3 to 4 hours             | 3     |
|                                                               | 4 or more hours          | 3     |
|                                                               | [no answer]              | 4     |
| With whom do you play videogames most often?                  | By myself                | 11    |
|                                                               | With family members      | 2     |
|                                                               | With online friends      | 4     |
| What type of game do you play most often?                     | Text-based games (MUDs)  | 3     |
|                                                               | Audiogames               | 11    |
|                                                               | Mainstream games         | 3     |
| What assistive technology do you use when playing videogames? | NVDA screen reader       | 13    |
|                                                               | Other PC screen reader   | 1     |
|                                                               | In-console screen reader | 2     |
|                                                               | None                     | 2     |

puzzle games (4), trivia games (3), educational games (3), racing games (1), and horror games (1).

#### Qualitative data from the online survey

Our analysis identified different aspects of the gaming experience that respondents enjoy. Two respondents referred to the narrative of the game: "the great narration and stories you're able to find, plus the regular updates" (Carlos), "Story and actions" (P2). Others highlighted the level of complexity of the game: "The combination of exploration/discovery with the challenge of survival" (CJ), "Plenty of areas to explore, with new ones being added regularly" (P3), "Complexity, attention to details, and replayability" (P6), and "The mainstream-like feel" (P4). These answers foreshadow some of the themes that reappeared in the follow-up interviews.

Respondents were asked about the cues that games use to convey information. Our analysis identified three modes: text, sounds and radar. Text referred to the ability of the digital game to present information in such a way that is compatible with screen-reader software. Sounds referred to the use of auditory icons and earcons across digital games, and radar, as explained by P4: "functions like a cane, playing different sounds if it finds open space, walls, or other objects".

Respondents were asked about their experience with AR and VR. None of our respondents had experienced VR before; however, P7 said they "would be open to it if it could even work for me" and Juan "would really like to [try VR]!". When asked if they had tried AR experiences, four respondents claimed to have tried the popular *Pokémon Go* game and found it completely inaccessible. In the words of one of our respondents: "of course the development team had not considered the fact that a blind person may be able to play".

#### Follow-up interviews

The semi-structured follow-up interviews allowed us to explore in more depth the opinions and concerns of GVI. Key themes related to: the personal appeal of games—what participants found engaging, or the story elements that they preferred; the social and gaming trajectories and relationships that bring them into and keep them in the gaming hobby; the way that they are represented in games; the perceived tensions around complexity and accessibility; and the challenges and promise associated with new technologies.

*Engagement in games.* Analysis revealed there were several factors that attracted GVI to games, namely curiosity, engagement, and ability to affect the game narrative. Marcela was driven to digital games by curiosity: "I was just curious about playing games, because I know there's a lot of games for sighted people and I was curious about how about us? How can visually impaired play computer game?". CJ was attracted to games because of the "engagement" games provide: "It's kind of hard to explain I guess. It isn't necessarily how complex, or intuitive, or anything like that so much as how engaging the game is". On a similar note, Juan linked engagement to the opportunity to direct the game's narrative, commenting that "affecting the story" keeps him engaged: "I don't even need a massive world, or anything like that, just something that feels important, like I'm doing something, like I'm affecting the story, you know?".

Engaging both GVI and sighted players was a challenge recognised by Juan: "[An audiogame] won't appeal as much to sighted people, there's almost no way to please both, which kind of sucks". Alberto, however, had a different opinion: "let's use *Swamp* as a good example. Again, because *Swamp* has minimal, but still it has graphics. And, I have lots of friends, and nephews, and a bunch of sighted players playing alongside us".

Analysis revealed that engagement changed over time as the visual capabilities of players changed. CJ explained that they "got better at *Mortal Kombat 4* after I lost my remaining vision, because I wasn't distracted by how difficult it was to tell things apart". This range of different forms of engagement that GVI enjoy in games highlights the need for a diversity of game styles and interaction methods.



*Stories and narrative.* Some of our participants considered the story a key element for videogame engagement. For Juan, games where he affects the story were "the kind of genre I would like the most", but "there's very few audiogames that really have a story". Juan commented that he particularly enjoys MUDs because "they've got lots of story". Carlos shared this sentiment:

"the more story there is and the more control you have over it, the better it is in my opinion. So, I really like story driven games. There aren't that many audiogames that change based on your decision unfortunately, but the ones there are, I enjoy a lot".

On a similar note, Jose said: "in audiogames so far, we haven't really had much story stuff. It's usually just gameplay elements or it's a very minimal story". For these players, the game narrative supports and extends the gameplay experience.

*The tension of complexity vs accessibility.* Participants described a tension between a game's complexity and its accessibility. According to Juan, "You've got to make a game more crap if you really want to make it easier for blind people. You've got to make it more simplistic." In his opinion:

"Most games for blind people are made by someone else that isn't blind or hasn't been a gamer for a long time. [Games for PVI] are just really easy and simplistic when you actually get down to the action elements. They... are usually quite easy and don't have much challenge or replayability to them."

Alberto, on the other hand, noted: "You don't have to force a downgrade on a game just for it to be accessible". CJ cited a different issue when handling complexity, noting that "There are like some types of games where they use challenges that don't really map very well to audio in terms of their complexity and their speed."

Juan and Alberto both provide examples to support their opinion. For Juan:

"AHC [*A Hero's Call*], no sighted person would give a damn about that game. They'd be like, 'Oh, that's cool, it's playable for blind people', but no sighted person would be like, 'I want to play a game that basically uses modern sounds but has the whole game systems and story and stuff from the nineties'".

Referring to *Swamp*, a game with minimal graphics, Alberto said: "So, it's basically everyone on the same ground, there are no advantage for being sighted, or for being visually impaired in the game."

Older games were perceived as simpler by CJ, although this perception may be coloured by deterioration in vision:

"there was a period where I had some vision. It was still really limited... but I could see well enough to play *Mario* and games like that where they were not necessarily too deep, where the graphics were simple with the cartoonish colours and the not overly complex".

Players' perceptions of the relationship between game complexity and accessibility are clearly linked to the types of games that they play as well as to the situation of play.

*Social trajectories and gameplay.* Interviewees were introduced to different types of games by different people. In the case of Juan, "My dad [who is also blind] played [audiogames] a bit... sometimes I'd watch him play something". However, a different person introduced Juan to mainstream games: "I have a very good [sighted] friend but I barely ever see him anymore... he's basically my only access to mainstream games... and we would play *Super Street Fighter*, which I was never very good at, and *Mortal Kombat*, and *Injustice*". Marcela was introduced to audiogames by a friend: "at the end of year 2016, I was invited by my friend ..., and from there, I learned lots of games". It was similar for Alberto: "We tended to watch our friends, and family play when we were younger, like *Resident Evil*, *Silent Hill*, and stuff like that", and for Jose "I was over at a friend's house and he told me about [MUDs]". CJ, however, was introduced to games by a professional worker: "My brailist at the time introduced me to audiogames. The person who would translate my school work assignments into braille, had a bunch of kind of random software that they gave me".

According to Juan, the community of GVI is quite close. In his words:

"there's three or four games that blind people really tend to gravitate towards right now. *Swamp*, *Redspot*, *STW* [*Survive the Wild*], those three. You're almost guaranteed to find people that you find on audiogames.net and that you email or Skype with. It's a close-knit community. Everybody pretty much knows everybody or can remember them if they talk to them for a little bit".

Marcela said that when online, she "plays with her friends" and "has no experience playing with strangers". Similarly, Carlos plays with online friends, but he also plays "with a couple of people I know, IRL [in real life]". Marcela added that "we play together [with online friends] and sometimes just talk about random things". In these comments, interviewees have shown the value of social relationships in gameplay, the need for a gate-keeper, and a sense of community.

*Self-representation in games.* Participants had different attitudes regarding self-representation in videogames. In Juan's opinion, "I'm not into role players, so I don't really care about avatars. I just choose a username that I use on other stuff so that people know who I am, and I can find friends easier than I already know". Similarly, Carlos explained that in the game *Crazy Party*, "The name is the only way [to identify other players]". Referring to a first-person RPG called *Dark Passenger*, Alberto mentioned: "[the experience] is more immersive, because you are from the character's perspective. You are on the character's skin".

CJ highlighted the limitations for self-representation provided in audiogames:

"Something that I kind of wanted to see, but I'm pretty sure it isn't actually never going to happen is that there's a bunch of different types of armour in the game. It would be things that can have really distinct sounds when the players are moving. There's a leather jacket versus plate armor versus a SWAT armour. They're all like really different. If you were to have the sounds of that with the players' movements, I think that would make it a lot more interesting because you could hear people sound quite distinct... But it's still something that I think would help a lot with distinguishing characters, keeping them unique."

In this way, GVI could be identified by personalized audio icons or avatars.

*Accessibility in mainstream platforms.* Overall, participants showed positive attitudes towards accessibility in mainstream platforms. Carlos noted, "I love the fact that things are happening now. There has been a large step forward in accessibility in the last year and a half. We still have a long way to go, but it's like what's there is already great". Alberto felt the same way: "It's improving slowly, but it's better than nothing, I guess", and so did Jose: "I think it's getting better, but, of course, there's still room for a lot of improvement." Juan and Carlos both cited the Xbox as example of good accessibility decisions from mainstream companies. Carlos highlighted the following: "Just recently, the first TTS (text-to-speech) game for Xbox got released... Even if it's just a *Solitaire* game, it'll show other developers that this is possible, and they can do this". Juan praised the Xbox Accessibility Controller for its mainstream-like implementation and aesthetic:

"They took time to make it cheaper and also gave it a lot of ports. They made it not insulting in its branding or its marketing and they made it cool looking, which is pretty big. I thought, 'hey these guys took a lot of time to do that, that's awesome'."

Alberto talked about EA as a company that was concerned about accessibility: "We have big companies like EA. They are very concerned about how the games they are producing are getting to the public. So, a few games like *UFC [Ultimate Fighting Championship]* are getting accessibility treatment".

CJ, Alberto, Carlos and Jose agreed that fighting games "are very accessible from out of the box" (Alberto). Jose explained how these games were made accessible: "The menus are now read out loud... I was listening to other people playing the latest *Mortal Kombat* games and they have different sound cues to let you know when certain things happen".

Our participants also acknowledged platforms that are not as accessible. Juan noted that "Steam is a nightmare to get around". Regarding the game development platform Unity, which is not accessible to screen-reader users, Carlos said "If we had a language as powerful as Unity without the accessibility problems, we could have some really good games out there already". Our analysis showed that participants were well aware of the steps towards accessibility that the gaming industry is taking, as well as particular environments that were problematic for GVI.

*Experience with virtual and augmented reality.* Our analysis revealed that, while our participants have not had any experiences with VR, some yearned to try these technologies. Marcela expressed her desire to participate in VR experiences. She said, "I really wish there was a game like that", referring to the combination of head-tracking and 3D binaural sound. "3D sound is more fun so that you can imagine you're 3D playing on reality and not just computer". CJ saw potential in the ability of VR headsets to track a person's head: "I have figured if you actually have head tracking, it would be easier to keep track of how you're oriented, so that would probably help."

Carlos had experience with the popular AR game *Pokémon Go*. He described the experience as follows: "With VoiceOver [the default screen-reader in iOS], it is completely inaccessible, so you have to have someone else there. And they just played, and I just watched and went with them... It would be something I would really love to play if I could". His final comment on the issue was this: "My main concern with VR and AR is that it will leave blind gamers in the dust even more, as things transition to very VR-based games and simple graphical games aren't enough anymore".

## 6 DISCUSSION

Technology is often seen as a means to 'normalise' individuals with an impairment by compensating for what are presented as deficits [78, 79]. Rogers and Marsden have argued that the rhetoric of compassion that underpins this approach to research can lead researchers to design technologies which they think the disabled person needs [91].



This worldview can alienate the person with a disability, making their true desires and aspirations secondary to their bodily limitations. Instead, researchers have recommended that the HCI community should follow a rhetoric of engagement and discourse of passion, and design for empowerment rather than compassion [79, 91]. Following this path could enable relationships with technology that are "neither mastery and control nor passive acceptance, but an experience of being immersed in intimate interactions" [79]. Indeed, our participants demonstrated a passionate relationship with their games, playing from a very early age, some dedicating more than four hours a day to playing videogames or, in the case of Carlos, playing the same MUD for over thirteen years.

### The importance of games to PVI

Our participants rely heavily on audiogames, which offer an accessible, familiar, and enjoyable interface for their gaming. They describe their engagement with games and can recount their personal histories of gameplay. Survey respondents invest considerable time in gaming, with two thirds of respondents playing games at least every other day and eight of thirteen respondents playing for two or more hours at a time.

Playing games is a goal-directed leisure activity [81]. Studies of "Gamer Identity" have found that needs for competence, autonomy and relatedness are closely correlated with the individual's social identity as a gamer, and that enjoyment and connectedness are important to both casual and heavy gamers [81]. This is echoed in our interview data through the discussion of the particular activities and game elements that participants found engaging, as well as in the way that they described their experience of sociality.

One topic that did not appear in our findings was any desire on the part of the interviewees to present themselves as a blind character in-game, although Carlos commented that there are stereotypical blind characters in *AHC* and *Blind Legend*. It was unclear whether this was due to the desire to present an idealized self (as shown by some older adults [26]), whether it was an oversight, or whether it was due to a lack of in-game supports for blind characters. Research with young people using powered wheelchairs suggests that although users with a disability might not prioritise representation of that disability in an interface, they may nevertheless value that representation if it exists [49].

### Social play

Gaming is known to be a highly social activity [41]. There is a considerable body of research that explores the dynamics of groups on MMOs and argues that multiplayer capabilities improve or extend the gaming experience [28, 39, 101, 114].

Moreover, others have argued that social interactions in digital games are beneficial to gamers' social networks in the virtual world, as people establish and maintain social ties [103, 121]. Game aficionados frequently get to know others in-game [40, 101], accruing social capital through group membership [33, 110]. Comments such as Marcela's observation in the section *Social trajectories and gameplay* that sometimes she gets together with friends to play but instead talks "about random things" echo similar reports stressing the sociality of gaming, describing face-to-face gaming evenings "where no actual gaming took place because we just started talking and had a fun evening." [92].

Participants described the trajectories of their involvement in gaming. Many talked about the people—friends, family or professionals, who introduced them to games and who played with them. Juan, for example, described a sighted friend, who he no longer sees regularly, as having provided his "only access" to mainstream games.

Many of the games our participants engage with have multiplayer capabilities. With one of our participants defining the community of GVI as "close-knit", future research could explore in more detail the types of social interactions that are targeted to GVI. For example, research on streaming play typically focuses on the technology [1, 116], the selection of games [34], the visual spectacle [102], and on chat interactions [99]. In our interviews, however, Jose described listening to other players playing *Mortal Kombat*, observing that sound cues may help provide an even ground for players with different physical abilities.

### Mixed-ability players

Although we found some research interest in audiogames [66, 90], there is little to no research that examined the involvement of sighted players in audiogames, or of players who also experience another form of impairment such as hearing loss. Both of these groups are identified in a post to the audiogames.net forums by the designer of *Swamp*, who notes the additional accommodations that he has designed for blind players with hearing loss, and that he has made changes to improve accessibility "for our minority player-base, and by that I mean those silly sighted players" [5].

We found disparate views from our participants about whether games can be designed to be both accessible to GVI and challenging for sighted players. Given this, it would be valuable for future research to explore the thoughts of sighted players regarding audiogames. Games like *Musicraft* demonstrate that it is possible to design audiogames for both VI and sighted players [66], although these have yet to become mainstream. Moreover, it would be interesting to explore the interactions between sighted players and GVI, as well as the experience and needs of players with multiple impairments.

Two recent industry reports [20, 42] found that a large percentage of gamers are children and teenagers. This points to a need for further research on this group of players, which could explore the dynamics and needs of younger GVI. Moreover, we received five responses from GVI aged under 18. Because of constraints around our ethics approval, these respondents were not allowed to answer the questions of the survey once they identified their age, but this interest shows the eagerness of younger GVIs to share their views on digital games and accessibility.

### Reducing barriers to play

Tensions of PVI integrating to mainstream activities such as regular employment, and the workarounds they rely on have been explored in depth [109]. Additionally, projects have proposed both general guidelines for accessible game design [58] and more specific guidelines, for example the *Meeple Like Us* guidelines to accommodate PVI playing tabletop games [59]. These efforts show that with the right support and adaptations PVI can participate in any gaming activity regardless of their impairment. As Alberto puts it, with the right support "basically everyone [is] on the same ground, there are no advantages for being sighted, or for being visually impaired". This equal footing may enable PVI to experience the immersive interactions associated with the discourse of passion [79] in the same way a fully able-bodied player engages with games.

While the research community has made many efforts to address the gap of inaccessible games, with examples such as *PowerUp* [103] or *Blind Hero* [117], these usually fail to reach the mainstream [86]. Given the renewed interest of the game development industry in producing accessible games, as explained by our participants, there is an opportunity for industry and research to find new and imaginative ways to reducing barriers to play.

### Realistic auditory representations

Extensive research has explored the role of avatars as mediators of interactions with virtual worlds [25, 26, 62, 87]. Visual aspects of avatars have driven much of this research [38]. Studies have explored the use of photorealistic avatars [87], avatars with expressive facial animations and real-time hair simulation [24], and avatars with customisable walking gait [80]. However, little to no attention has been placed to the aural customisation of avatars. As CJ explained, providing unique sounds to players based on specific game elements such as armour "would make it a lot more interesting because you could hear people sound quite distinct". We believe there is an opportunity to explore the impact of providing aural customisation of avatars to both sighted and VI gamers.

### Lack of complexity

Our participants valued complexity in games, although some felt that games for PVI tend to be overly simplistic. A possible reason for this perceived simplicity could be the tendency for sighted individuals simulating VI to consistently underestimate the capability of players living with VI [98, 100].

One difficulty in extending complexity is the fact that images are persistent, where sound has a distinct beginning and end. In order for a sound to persist, it must be repeated. This adds to audible clutter and, thus, to the cognitive load required to understand and play the game. Further work is required to understand the balance between providing enough sound to support GVI and over complicating the process required to understand the game state [68].

### Concern about emerging trends

Two recent surveys [20, 42] provide a detailed analysis of gaming trends in the US and Australia, highlighting trends within the broader gaming community which may affect GVI. Both reports note a growth in the use of VR devices, with one report suggesting that "1 in 3 of the most frequent gamers said they were likely to buy VR in the next year" [42]. This contrasts with the attitudes and thoughts of our participants, who have had no experience with VR and fear that this technology would "leave blind gamers in the dust even more". This suggests that accessibility features are not keeping pace with the speed of technological change, aligning with concerns that even existing accessibility technologies fail to capture the broad range of experiences and interactions available to sighted players [100].

### Longevity of older technologies

The first MUD is documented to have appeared in 1978, as networked computing became popular [13]. Through the 1980s and 1990s, MUDs were associated with technical prowess and unruly university students misusing valuable network resources [12, 43]. However, as computing moved towards graphical user interfaces, MUDs evolved into MMORPGs [13]. While it is hard to imagine sighted players engaging with text-based games that are built on forty-year-old technology, MUDs have found a new player base in the community of GVI.

Reflecting the importance of narrative to these players, Carlos, Juan, and Jose agree that MUDs allow for the creation of richer stories than most audiogames. This highlights the importance of applying a multi-modal approach to communicating the state of the game world and the available options. The text-based interface, which is compatible with the screenreading technology that PVI are already using in other aspects of their lives, is particularly well-suited to the audiogame format and allows interesting narrative and

gameplay without restricting the complexity of the story and interactions.

## 7 CONCLUSIONS

In this paper, we have exposed the habits, opinions and concerns of a group of gamers with visual impairment (GVI). We have found that, just like their sighted counterparts, GVI build diverse histories and social trajectories through gameplay. However, unlike their sighted counterparts, GVI must confront a series of barriers to gameplay: limited options of self-representation, a perceived lack of complexity in games, the necessity for engagement with decades-old text-based technologies, and fears of being “left in the dust” by new and emerging technologies such as VR and AR.

By exposing these concerns, we hope to inspire future work that pays closer attention to the needs of diverse groups of players. We expect that this work will create awareness of the need for a rhetoric of passion, where deficit-driven design is tempered by a positive-design approach that focuses on empowering immersive and enjoyable interactions that are equivalently accessible to both PVI and sighted players. Rather than seeing disability as something that needs to be normalised, this approach recognises the skills and knowledge of PVI and demonstrates the practices and opportunities that GVI communities are already embracing.

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## 4.5. Discussion

The paper presented in this chapter explores the following issues regarding the relationship between gamers with visual impairment and digital games:

- It identifies trends regarding how gamers with visual impairment engage with digital games. Particularly, it highlights that more than half of participants engage with digital games every day or every other day; the length of their playing sessions is usually of two hours or more; they play mostly audiogames by themselves and use the screen-reading software NVDA to access digital games. These trends had not been uncovered before.
- It establishes the importance of games in the lives of people with visual impairment by describing the reasons why gamers with visual impairment engage with digital games in the first place. These reasons include: because people with visual impairment enjoy the game narrative and the ability to affect the story; because they were curious about games in general; and because they liked the “engaging” experience. Moreover, the paper highlights the social interactions afforded through digital games.
- It highlights a tension between making a game that is accessible but at the same time challenging. This suggests that people with visual impairment are craving for the development of experiences that are equitably accessible (Smith & Nayar, 2018). In such experiences, gamers with visual impairment would not be singled out because of their disability and would be able to participate in gaming experiences with others without being excluded (van de Ven et al., 2005).



- It determines a perceived two-fold threat to gamers with visual impairment related to new and emerging technologies: on the one hand, gamers with visual impairment still rely on decades-old technology such as text-based adventures, as in many instances this technology is accessible by default. On the other hand, gamers with visual impairments fear that new technology, such as virtual and augmented reality, would prevent them from accessing games, as these new technologies are perceived to be inaccessible. In their own words, gamers with visual impairment fear to be “left in the dust even more”.

Overall, these findings provide unique insights in the habits, opinions and concerns of gamers with visual impairment. Rather than conceptualising visual impairment as a loss that needs to be compensated for (Shakespeare, 2013), the findings presented in this chapter recognise the resilience and unique skills developed by gamers with visual impairment as they engage with digital games. More broadly, this paper provides a series of themes informed by expert gamers with visual impairment that are relevant to future researchers and game developers when designing games that are accessible.

Months after the publication of this paper, its methodology was replicated by Urbanek and Güldenpfennig (2019). Their study corroborated some of the findings presented in this chapter. Urbanek and Güldenpfennig (2019) made similar findings regarding the social aspect of the gaming experience of gamers with visual impairment, the tension between making games that are accessible but challenging at the same time, and the concerns about new and emerging technologies. This highlights the newfound interest of the research community in the experience of gamers with visual impairment.



In the next chapter, I continue to present more results from study 1 and continue to explore RQ1: how do gamers with visual impairment currently engage with digital games? However, the focus of the analysis in the next chapter will be different. While this chapter is concerned with *the gamers*, the next chapter explores the elements that, according to expert gamers with visual impairment, make games accessible.



# Chapter 5: A Framework to Understand Accessibility in Digital Games

## 5.1. Introduction

In this chapter, I present a second paper based on data collected as part of the semi-structured interviews that comprised study 1. This paper continues to explore how people with visual impairment engage with digital games (**RQ1**) as a means to construct a holistic understanding of the relationships between people with visual impairment and digital games. While the previous chapter focused on the habits, opinions and concerns of a group of expert gamers with visual impairment, the analysis of this chapter focuses on the common key elements that gamers with visual impairment identify as necessary for games to be accessible. These key elements have been ordered into the Gamer Information-Control (GIC) framework. Just like chapter four, this chapter aims to foster a discourse of empowerment (Rogers & Marsden, 2013), by giving voice to an underrepresented group in academic literature and by recognising the unique skills that gamers with visual impairment have developed through their lived experience.

This chapter provides a new analysis of the data first presented in chapter four and incorporates parts of the data set that did not fit in the previous analysis. This new focus

of the analysis revealed that relationships with in-game information and relationships with elements of control are key to accessibility in digital games for people with visual impairment. These two relationships and specific instances where these are salient have been condensed in the GIC framework. Moreover, these two relationships are present both when gamers are acting as players or as creators. This framework provides a novel way to discuss accessibility in digital games by not focusing on individual games—as is the case with a large portion of research in accessibility and digital games—but rather learning from expert gamers with visual impairment about the elements they consider most important when making accessible games.

The paper presented in this chapter is titled “Introducing the Gamer Information-Control Framework: Enabling Access to Digital Games for People with Visual Impairment”. The paper was published in the *Proceedings of the 2020 CHI Conference in Human Factors on Computing Systems*. Although the conference was cancelled due to the COVID-19 health crisis, the paper was published in the Association for Computing Machinery Digital Library (ACM DL). Prior to its publication, the paper underwent rigorous review by three anonymous reviewers and a meta reviewer. The paper is included in this chapter following the format of the publisher. Similar to the paper presented as part of chapter four, the references cited in the paper are included within the paper instead of in the References section at the end of this thesis.

### 5.2. How this paper contributes to the thesis

The paper presented in this chapter continues to explore **RQ1**: how do people with visual impairment engage with digital experiences? The analysis of the paper focuses on the games people with visual impairment play, and the elements that, according to the

players, make these games accessible. The main contribution of this paper is the introduction of the Gamer Information-Control (GIC) framework. This framework emerged by focusing on the key relationships that enable people with visual impairment to engage with digital games. Similar to the paper presented in chapter four, the paper presented in this chapter encourages an interactional understanding of the experience of visual impairment and digital games, where the presence or absence of specific game elements may prevent people with visual impairment to engage with these games (Shakespeare, 2013). Key to this thesis is the finding that conveying spatial information is critical to ensure accessibility in digital games for people with visual impairment.

Similar to the paper presented in chapter four, this paper fosters a discourse of empowerment by relying on expert gamers with visual impairment to identify key enablers to their gaming experience (Rogers & Marsden, 2013). This paper provides an opportunity to reflect on existing affordances that people with visual impairment have found useful, and elicit new affordances to mediate the acquisition of in-game information and the interplay between different control elements.

### **5.3. Data collection and analysis methods**

The paper presented in this chapter follows a qualitative methodology, with in-depth semi-structured interviews used for data collection, and thematic analysis used for data analysis. While chapters four and five draw from the same interview data, none of the raw data—in the form of interview quotes—presented in this paper was used for the paper presented in chapter four. This is because, upon analysing the interview data, it became evident that participants' comments could be categorised into two overarching categories: their general opinions about being a *gamer* with visual impairment—discussed in chapter

four—and their opinions on what makes *games* accessible in the first place. Once that distinction became clear, it was necessary to analyse these two overarching categories separately; hence the need to produce two separate publications based on the same dataset. Moreover, the production of several academic articles to broaden the understanding of how gamers with visual impairment engage with digital games aligns with the notion that in a critical realist context knowledge should be made available to be shared, as explained in chapter three.

The raw data from the interviews were analysed using thematic analysis, as described by Braun and Clarke (2006) and Braun and Clarke (2012). This analysis revealed that the elements that enabled gamers with visual impairment to engage with digital games included: comprehensible representations of 3D space; metaphors for representing real-world objects and phenomena; elements external to the game itself, such as screen-reading software or alternative hardware accommodations; the prevalence of text as a way to convey information and allow for game control; and the role of gamers as creators. Further reflection on these themes led to them being regrouped as functions of key relationships between gamers and the games—relationships with information provided by the game and relationships with elements of control—and became the Gamer Information-Control framework presented in the paper.

### 5.4. The paper

A PDF file of the paper can be found at <http://go.unimelb.edu.au/3d9j>.

## Introducing the Gamer Information-Control Framework: Enabling Access to Digital Games for People with Visual Impairment

**Ronny Andrade**

The University of Melbourne  
Melbourne, Australia  
andrader@unimelb.edu.au

**Melissa J. Rogerson**

The University of Melbourne  
Melbourne, Australia  
melissa.rogerson@unimelb.edu.au

**Jenny Waycott**

The University of Melbourne  
Melbourne, Australia  
jwaycott@unimelb.edu.au

**Steven Baker**

The University of Melbourne  
Melbourne, Australia  
steven.baker@unimelb.edu.au

**Frank Vetere**

The University of Melbourne  
Melbourne, Australia  
f.vetere@unimelb.edu.au

### ABSTRACT

In this paper, we present a foundation for understanding the elements that enable people with visual impairment to engage with digital games. This is defined by the gamer's relationships with information and with elements of control provided by the game, and is mediated through in-game metaphors and affordances when gamers interact as users or creators. This work complements previous research exploring the points of view of gamers with visual impairment by focusing on the games they play and prioritising the relationships between the key enablers of access to digital games. Using the framework to examine existing and missing components will enable designers to consider broader aspects of accessibility in game design.

### Author Keywords

Visual impairment; digital games; audiogames; control; information; framework

### CCS Concepts

•Social and professional topics → People with disabilities;  
•Applied computing → Computer games;

### INTRODUCTION

With two out of three Australians playing videogames, and an estimated 2.5 billion videogamers around the world [18, 88], it is important that digital games be made accessible to all regardless of physical abilities. The visual nature of digital games—embodied, literally, in the name videogames [10]—renders them mostly inaccessible to people with visual

impairment (PVI). This produces feelings of exclusion [79, 94] and of "being left in the dust" [6].

Current research on games for PVI typically focuses on the introduction of a single game as a case study in which researchers present the game to gamers with visual impairment (GVI) and evaluate its use. *Shades of Doom* [90], *Blind Hero* [93], *PowerUp* [84], *Swamp* [8], *VBGhost* [55] and *BraillePlay* [56], are some of the games that have been introduced in this manner. This approach has generated many games that offer ongoing enjoyment to GVI. However, to identify the common elements that make a game accessible or prevent access to it, a broader understanding of such elements is required. Works such as that of Urbanek [85] and Andrade et al. [6] represent attempts to take a broader look at games for GVI. Nonetheless, these works focus on describing the experiences of GVI rather than on reflecting on the common elements that enable and support access.

In this paper, we propose a framework for understanding the elements that enable PVI to access digital games. We show that gamers' relationships with the information provided by the game, and with elements of control, are key to enabling access to digital games for PVI. These relationships are mediated through in-game metaphors, and extend beyond play to encompass creation activities. With this framework, we provide a broader way of thinking about design of games that are accessible to PVI. Our approach is independent of the game being studied, has been developed through an inductive process, and has been informed by in-depth semi-structured interviews with expert GVI.

This work continues the move away from a deficit-driven approach to understanding games towards a more positive approach which embraces and respects the voice, lived experience, and expertise of PVI [6, 57, 67]. It explores the relationships between the different elements that comprise the gaming experience of PVI. In doing so, our work recognises how the elements of game design influence our understanding of the complex, nuanced requirements of disability and ac-

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cess [72, p. 72–75]. This approach allows HCI researchers to focus on designing and understanding interactions, removing the need to appropriate technologies as well as physical and other impairments, as is the case when researchers attempt to emulate the experience of PVI [14, 67, 73].

#### AIMS AND CONTRIBUTION

The main contribution of this work is the presentation of a framework to understand the elements that enable people with visual impairment to access digital games. These include two key relationships and a set of in-game metaphors that support these relationships. Whereas previous research has provided an overview of games commonly played by PVI [49], or has explored the opinions, habits, and concerns of GVI [6, 85], to the best of our knowledge this is the first attempt at providing a broader exploration of the elements that enable PVI to access digital games. With this research, we aim to provide a tool for game designers and researchers to think about the key relationships that enable PVI to access digital games. The elements of this proposed framework are derived from interviews with expert GVI that recognise their knowledge and skills developed through lived experiences of disability and gaming, thus advancing empowerment approaches over deficit/compensation perspectives [58, 67, 72].

#### LITERATURE REVIEW

This work builds on current understanding of games, gamers and game play through a nuanced discussion of the gamer's dual role as player and as (potential) creator or co-producer. It builds on prior work with GVI and understanding of disability, as well as broader HCI contexts of affordances, metaphor, materiality, and embodiment, and is situated in the study of games and play.

#### Disability

There has been recent interest in HCI in the needs and practices of GVI [6, 29, 85] and, more broadly, of PVI [21, 33]. This work raises questions of inclusion and empowerment [71] and examines the challenges faced by different groups and the technologies that support and enable them. Our framework describes the relationship between the player and the real-world tools that may be adopted and appropriated as in-game metaphors. In particular, we consider the representation of echolocation as an in-game metaphor.

#### Echolocation

Echolocation is a technique that combines production of sounds with an understanding of how those reverberate over surfaces and the time delays of the echoes produced to create a mental image of the physical surroundings [5, 50, 77]. Like bats and some aquatic mammals [81], up to 20–30 per cent of people with visual impairment can use echolocation as a tool for depth perception and navigation as well as for understanding the properties of specific objects [77, 80].

Although there has been some exploration in literature of games and game-like tools for teaching echolocation [23, 91], and on the use of echolocation to provide additional in-game context —Haahr [37] describes a game for sighted players in which the player takes the role of a blind character who

must use echolocation— there has been comparatively little research attention on the use of echolocation as a supplementary or alternative in-game method for navigating game spaces. Preliminary studies [5, 91] have shown that PVI can successfully locate specific targets in virtual worlds through a combination of pre-recorded and dynamically-generated echoes and binaural sound. The player's relationship with in-game tools for echolocation is a core element of our model.

#### Games

##### Audiogames

An important genre of digital game that enables play by GVI is audiogames. These games feature "complete auditory interfaces, so that they can be played without the use of graphics" [34]. Audiogames use earcons, abstract artificial sounds or sound patterns with varying metaphors and levels of articulatory directness [31, 42], to convey information to players. Unlike videogames, which frequently feature similar interface elements and metaphors to represent objects and actions, there is no consistent set of earcons used across different audiogames, even for common tasks such as saving a game or confirmations [6]. Players must learn a new set of earcons as they learn a new game [34]; this increases the cognitive load involved in play as the player must focus on understanding these signifiers rather than on the potential for controlling novel and creative actions that they may [be intended to] afford.

##### MUDs

Text-based MUDs, or Multi-User Dungeons [10, 12, 75], are another popular choice for GVI. Because these games provide information and are controlled through text, they represent an accessible option, despite not being specifically designed for PVI. Spiel et al. [75] identify a number of opportunities to improve the accessibility of these games for GVI. Specifically, they found differences in the ways in which sighted players and GVI used in-game navigation systems in different types of spaces, with GVI generally preferring egocentric systems which represent directions in relation to the player (go forwards, turn right) and sighted players preferring systems which referenced cardinal directions (go north, west, etc). These findings highlight the importance of the relationship between the player as user of the game and the game's controls, even on text-based interfaces.

##### Affordances and Metaphors in digital games

The affordances of an object are the "potentials for action" that a user can perceive [35]; an affordance is a relationship between a person and an object [60]. Interfaces are said to have *perceived* affordances. Elements of digital games afford a specific range of in-game actions, for example, jump / pick up item / open door / fight / move in a particular direction / use item. Signifiers — such as a door handle, 'enemy' icons, compass arrows or a bag — communicate potential behaviours to users [60]. When these are clear or familiar, the cognitive load on players is reduced, but poor or non-existent communication, or an overly-literal metaphor, complicates or obscures the potential for action [59]. Moreover, a game communicates "social affordances" [28] or possibilities of interaction with other players, and may present "motivational affordances" that



satisfy the player's need for competence, autonomy, or relatedness, the core elements of Self-Determination Theory [13, 30]. As digital games rely on the visual sense to display signifiers — hence the name "videogames" — these signifiers and the affordances they embody may be lost to those who cannot see unless they are explicitly communicated to PVI [6].

Similarly, there are largely-unexplored tensions around the use of interaction metaphors in digital games [68]. Norman [59] notes that there are risks in adopting overly literal metaphors — for example, they may unnecessarily restrict the scope of interactions and limit creativity in design [36] — yet at the same time these literal metaphors "require very little explanation to users" [74]. Successful metaphors simplify the relationship between a player and a game in both accessing information and in operating, or controlling, the game by communicating affordances to players.

The absence of a consistent set of design conventions for audiogame design complicates and problematises the processes of both play and production, as it relies on the player to perceive the affordances of each situation without the benefit of prior experience with common metaphors. Moreover, it requires the designer to develop not only new interface elements but also new signifiers. Without a common set of interaction metaphors, the affordances and signifiers of each audiogame must be identified and learned before the player can proceed or advance. This creates distance between the signifier and the player [57], interrupting the player's sense of presence and immersion [53] and disrupting the potential for "instant sense-making" [38]. Further, it disrupts the relationship between player and game, disabling the player through the breach. This contributes, we believe, to players' criticisms that accessibility measures may also serve to unacceptably reduce game complexity [6].

#### *Co-production — Players as Creators*

Players and developers hold similar ownership of the game, with content creation by gamers helping to keep games fresh [41, 43, 62]. Through play, players create new information within the game-world. For example, they may move or remove objects or barriers, creating a new configuration of existing objects within the game space. Moreover, like sighted players [9, 62], GVI may take an active role in co-creating in-game content and are active in creating entirely new games [76, 85]. To date, there has been no research into the experience of GVI as creators of either games or game controllers.

#### **HCI Contexts**

##### *Materiality and Embodiment*

Playing a game is an embodied experience [46, 47]. The player interacts directly at an operational level with the game and its controller [26]. They are embodied as an in-game character [26] with the experiences and action potential of that character in a given situation [46]. For example, Haahr [37] describes a game for sighted players where the character that they play is blind. This requires the sighted player to take on the attributes of that character, navigating the game by echolocation rather than by sight. Similarly, GVI may be simultaneously sighted and non-sighted based on the attributes of the character that they control. This represents a design challenge, particularly

where the 'sighted' character's impressions and observations in a 3D space must be communicated and presented to a non-sighted operator. The player's body receives and mediates information and acts to control the game environment, and the game's inability to accommodate the bodies and abilities of GVI disrupts the experience of play.

In creating games, the material, operational properties of the game controller, in combination with the computational properties of the system, enable and prohibit in-game affordances for individual players [44]. Interaction in digital games for PVI has relied on the use of a keyboard [69, 93]. However, recent research has explored the use of mainstream game controllers to embody the interaction with a digital games, with positive results [25, 79].

#### **METHOD**

We conducted qualitative, semi-structured interviews for data collection, and used thematic analysis for data analysis. Our analysis focused on exploring the key relationships that enable the gaming experience of PVI. This study received Ethics approval from the University's Ethics Committee (Ethics ID 1851274).

##### **Data collection**

Data for this research was collected through online semi-structured interviews with a group of six GVI over the period of a week. These semi-structured interviews aimed to provide an in-depth exploration of relations between GVI and digital games. Questions asked during the interviews included: the type of games participants played, participants' opinions on existing metaphors employed in digital games targeted to PVI, their thoughts on the relationships between digital games and the computer systems where the games run, their experience creating audiogame-related content, and their perception on the challenges they face when engaging with digital games — both mainstream and targeted to PVI. Interviews were conducted over the internet, using the software participants felt most comfortable with. Five participants used the video-conferencing software *Skype*, and one participant preferred the audio-conferencing software *TeamTalk*. Interviews were audio-recorded and were scheduled to last for 20 minutes, however some participants chose to exceed the pre-established time limit to more fully express their views on their experience of gaming as a PVI. Interview recordings amounted to 186 minutes in total or 83 pages of transcribed material.

##### **Participants**

Participants were recruited through posts on [forum.audiogames.net](https://forum.audiogames.net), an online forum for that attracts a large number of GVI. A total of six participants agreed to take part in an interview. These participants were over 18 years of age and had a visual impairment that could not be corrected with glasses: blindness with or without light perception, or low visual acuity with mostly colour perception. All participants had been playing audiogames or MUDs five years or more, and spoke English as a first or second language. Four participants identified as male, one as female and one preferred not to disclose their gender. As participants were self-nominated, we were unable

Table 1. Demographic information of participants.

| N | Age range | Name    | Gender            | Country     | Impairment (and onset)                                                       |
|---|-----------|---------|-------------------|-------------|------------------------------------------------------------------------------|
| 1 | 18 to 25  | Juan    | Male              | Canada      | Blind, no light perception (from birth)                                      |
| 2 | 18 to 25  | Marcela | Female            | Philippines | Blind, light perception (early childhood)                                    |
| 3 | 26 to 35  | Alberto | Male              | Brazil      | Blind, no light perception (early childhood)                                 |
| 4 | 26 to 35  | CJ      | Prefer not to say | USA         | Blind, no light perception (10 years old)                                    |
| 5 | 18 to 25  | Carlos  | Male              | Austria     | Blind, light perception (from birth)                                         |
| 6 | 26 to 35  | Jose    | Male              | USA         | Low visual acuity. Colour perception. Loss of peripheral vision (from birth) |

to control for gender bias. Table 1 shows a summary of our participants, who are referred to by pseudonyms.

### Data analysis

Data were analysed using inductive thematic analysis, as described by Braun and Clarke [19, 20]: we initially transcribed the interviews, read and re-read their content, and established initial codes based on what was present in the data. Upon finishing this initial coding, we identified several categories or themes within the data. These initial themes were given a formal definition and a name. The first author coded data from all the interviews and the other authors coded specific interviews. This was done to ensure consistency amongst the themes established. Although different authors named individual themes differently, they identified similar concepts and ideas, thus showing agreement.

Importantly, thematic analysis is about the quality of the codes rather than about their frequency. A single instance may constitute a valid code, which then combines with other codes to generate a theme. Key themes in our data highlighted the important relationships that enable or prevent PVI to access digital games. [57]. We identified two key types of relationships that enable GVI to access digital games, which occur both when the gamers are playing (using) digital games and when they engage in creative activities.

### FINDINGS

In this section, we present the themes found as part of our thematic analysis. For findings regarding the types of games GVI played, the average duration of their gaming session and the genres they played, see [6]. The themes we identified mostly reflect representations of 3D space, representations of real-world objects and phenomena (radars, white canes, footsteps, echoes, spatialised sound, echolocation and walls), text as a means to convey information and control the game, and other enabling tools. Participants reflected on the nature of computers as complex systems, the metaphors they would like to see implemented in games and their previous experience engaging in creative activities related to digital games.

#### Representation of 3D space

Representing and understanding 3D space has proven challenging for GVI. According to Juan, who lost his sight during childhood, it is because “we don’t have that kind of... we don’t think that way, most of us”. Marcela explained how 3D games are presented to GVI:

*“In the blind community when we say 3D games, it means that you can walk up and down the map, unlike side scrolling games, where you only walk to the sides... In 3D games, you can use the four arrow keys to go through the map.”*

3D space in games may be demarcated by natural features, such as dense forest or precipices, or by ‘built’ elements such as walls and buildings. These determine where players are able to go and the routes they can take within the game.

For Marcela, the controls used in games that try to represent 3D space are a source of frustration. She said: “One thing that I don’t like sometimes with the 3D game is that instead of using arrow keys, they use A, S, D, and W. I want the 3D games to use just four arrow keys rather than other keys”. Representations of 3D space in games targeted to GVI seemed to limit players to four-directional movement, which was frustrating to some participants. Further, the controls provided in games are not appreciated by all gamers, particularly when a game requires players to learn a new set of controls (here: the A, S, D, W keys for movement rather than the more usual arrow keys).

#### Representation of real-world objects

Metaphorical representation of physical objects such as radars, tiles, white canes, footsteps or walls, were described by participants as means to convey in-game information. The game leverages the player’s experience and expectations of comparable physical objects in its implementation of these tools, although the outcomes do not always align with real-world outcomes.

##### Radars and white canes

Juan, Carlos, JC and Marcela described the use of radar-like systems for navigating audiogames. Their description focused on the radar system provided by games like *Swamp* and *Crazy Party*. CJ explained the operation of the radar as follows:

*“You can point it any direction, but it will scan five tiles or so. A tile is not incredibly defined as how big it is. It’s basically how far you’re going to step. You can adjust the range on it, so it could be just a few tiles ahead or it could be a lot further.”*

Carlos and CJ described the radar system akin to a “virtual cane”, and Juan added that “you can turn in 45 degree increments as well, 360 degree if you have a mouse”. Additional functionality of the radar system included tracking the position of other players. Marcela described this use of the radar system when talking about the MMORPG *Swamp*: “If you add the

characters to your party, you can hear a beep to your leader of the party. So, you can always know what is the direction the leader is going, and you can use a radar to know how far are the members from each other". Tiles, radar systems and white cane-like approaches provide GVI access to information about elements of the game world that are not immediately adjacent to their in-game position.

#### Footsteps and their echoes

Several audiogames use echoes to signify the presence of physical features such as walls, precipices or open spaces. Carlos described how such echoes are implemented: *"Mostly platformers use this. They signify that there is an edge by echoing your footsteps or by putting an echo near a wall"*. Jose, Juan and Alberto provided similar descriptions for the echo system and they identified the first-person arcade games *Sarah and the Castle of Witchcraft and Wizardry*, *Shades of Doom*, and *Planet Saga* as examples of games that use echoes to signify proximity to either a precipice or a wall. Alberto described the effect in *Sarah and the Castle of Witchcraft and Wizardry* as follows: *"when you're walking next to a wall for example, and we have an opening you have an echo towards the direction that the opening appears. So, you can turn away without bumping on the next wall"*. Juan added that *"in wide open spaces, you'll hear extra footsteps around you, just [to] sort of let you know that it's a wide-open space"*.

The use of echoes as a metaphor may not be akin to what occurs in the real world; however, these examples show that they are used to convey spatial information. Here, the same metaphor (the echo) signifies two distinct—and opposite—features. open spaces and walls have different effect on player characters, as one precludes and the other may encourage movement in a particular direction.

#### Representation of real-world phenomena

Participants described how real-life sound phenomena such as spatialised sound and echolocation are represented in videogames for GVI.

#### Spatialised 3D sound

This type of sound is used to approximate the human experience of sound in the real world as a player moves through or exists within a digital space. The appeal of this approach varied: for CJ *"[Spatialised 3D] recordings, those are usually really good, but you try to use the same effect in games, it's usually really not that good... it felt like they fell into the uncanny valley"*. However, Jose thought differently; he *"enjoyed the games themselves, the environments and the way the sounds moved around you realistically as if you were actually there"*. He thought *"that was very cool"*. These descriptions show that the relationship between GVI and 3D sound as a conveyor of spatialised information is experienced differently by each individual and may depend on the context.

#### Echolocation

Echolocation is the capability of some mammals, including humans, to use sound pulses and echo reverberations to create a mental picture of their surroundings [5, 50]. Our analysis showed that participants made a clear distinction between echo systems (described above) and echolocation capabilities.

This is a strong metaphor with profound connections to PVT's experience of echolocation in the physical world, which participants would like to see implemented in games. Nevertheless, they have some concerns about how this would be realised.

Jose, CJ, and Alberto use echolocation to an extent. CJ recalled their early experiences with echolocation: *"I had no idea what was actually going on, how this was working, but that was kind of always the thing that sort of got better over time"*, as well as later, more confident use of echolocation: *"when I was in college, I started to notice that I was able to tell where things were better if I was actually using the cane right"*. Jose recognized that *"the real problem with [echolocation] isn't just that you just hear sounds bouncing off things, is that you have some things that will block sounds too. It seems like something that would be really complicated for the computer to do"*.

The echolocation metaphor may provide GVI with additional valuable information about the game world as it does in the physical world. However, participants are aware of the technical difficulties of implementing this technique and of the skill required to master echolocation. Like other information sources, echolocation's utility is driven not only by the information to be conveyed (setting) but also by the user.

#### Game accessibility and assistive tools

Complex relationships exist between GVI and the devices that allow them to play digital games. Our participants described the complexity of computers and the relevance of alternative hardware solutions to mediate orientation.

#### Software interplay

Within the already complex architecture of the gamer's computer, the interaction between their accessibility software and the games is critical. Alberto noted that he liked *"to have the screen reader on at all times, because if I need to alt-tab to see another window and talk to someone else I can just do it"*. Carlos explained that certain games do not work with specific accessibility software: *"that is an issue of the screen reader itself because the screen reader, JAWS takes the keys and then steals the keyboard away from the application, so the game can't actually be played with it on"*. He also pointed out that this issue was more common in older games. In the case of Marcela, her first computer game *"actually is [a] game for JAWS"*. This has modelled her gaming habits. She said: *"As much as possible I look for games that work with JAWS... Maybe it's because JAWS was the first screen reader that I used"*. Accessibility software is an important factor of the overall gaming experience, as this software enables a person with visual impairment to control their computer—but this relationship is disrupted when a game is incompatible with a player's preferred accessibility software.

The complexity of the computer systems used by GVI was evident when Alberto explained how he communicated with other gamers: *"We tend to use means outside the game to [communicate]. We actually use Skype to, say for example 'let's regroup at the safe zone of map three, and let's explore from there'"*. This exemplified the complex interplay between player, screen-reading software, game, audio-conferencing

software and the computer's sound system. Additionally, CJ described risks of this complexity and stressed the importance of having games that run smoothly. They mentioned: "[the game] has to be able to work smoothly and stuff. If it's going to lag or crash all the time on my system, that's going to be a problem". Dourish [32] observes that computers are themselves prone to obsolescence and aging, and that software itself can be ephemeral in nature. The practices of GVI are therefore materially contingent upon the complex assemblages of computers and sub-systems that they require.

#### Alternative hardware solutions

Hardware solutions to improve perception of spatialised information are available. Participants commented about the SeeMonkey device. Alberto described this device as follows: "the goal of SeeMonkey is to connect to your headphone so the game can track where the direction you're looking at". His view on this device was that "if we can add this technology to an audiogame, we can emulate vision, sight. Because, we can have your character looking towards West for example, and the sounds from the other directions will be lowered". CJ was also familiar with the device, and added "the only real problem with it is keeping it calibrated... It had this tendency to drift really easily". In CJ's opinion, the combination of 3D binaural sound and head-tracking:

*"might work better, because one of the main things that was a problem with the more keyboard-controlled games is just orientation. You would turn and then you would run into a wall, and then you would try to turn to get around it, and you would have no idea what direction you're actually facing."*

Participants recognised that mechanisms that would enable control of the game beyond the keyboard could improve orientation in games and convey valuable spatial information to the player.

#### Making digital games more accessible

Participants identified a series of small changes and achievable targets that could create a big difference in accessibility in games. According to Jose:

*"when you're actually giving yourself a realistic target, you're still going to give blind people significantly more enjoyment in the game. People that really enjoy the game already, or even just enjoy listening to videos of it and playing it as much as they possibly can, are going to appreciate every single thing you do more than you might think."*

Alberto mentioned the following additional metaphors: "Coordinates are good for blind people, so are beacons... you can face the sun and that makes a tone if you're facing it and there's also a compass [mechanism]". Making text in menus accessible to screen-reading software was mentioned by Jose. Similarly, Carlos, who has more experience with MUDs mentioned: "all you really need to be able to play is a way for you to read the text, be this through self-voicing or SAPI or a screen reader". Other ideas included "audio cues to the meter bars like Ultra Street Fighter Four ... collision sound when you bump into a wall or objects" (Alberto), "ways to

turn down music and make action scenes a little less chaotic so there's not a million different things" (Juan). Participants have signaled the need for ways to convey more information and to have more control over the flow of information provided by the game.

#### Text as an interaction mode

Out of our six interviewees, Carlos and Jose had the most experience playing MUDs, with Jose "playing a MUD called Discworld MUD for well over 13 years". Jose described his experience in Discworld as follows:

*"The MUD is enormous. Including the terrains, I believe the MUD has over a million rooms. Some of the cities are quite large as well, which can make it difficult to find your way to where you want to go. After about 13 years of on and off play, though, it's not a problem for me anymore. I've built up mental maps of city layouts, where certain points of interest are, and some of the roads between cities."*

Jose's comment highlights how even relatively simple text-based games can foster long-lasting relationships of engagement while comprising a complex network of rooms, commands, cities, roads and more.

What attracted Carlos to MUDs was replayability: "if you want replayability and explore multiple facets of a story, then a text game is usually the better option"; and the ability to create the entire world with his imagination. "MUDs also draw a lot more on your imagination because it's just text. So you can imagine what the world feels and looks and sounds like". Similarly, Jose added that MUDs "really opened my eyes to the level of writing people could do that were just not professional writers". Carlos noted that "audiogames can be very fast paced and you don't really have that option with MUDs unless you have a sound pack". The appeal of MUDs may be due to the gameplay occurring entirely in the player's heads.

Not all our interviewees were fond of MUDs. Marcela said she doesn't "like dealing with MUD client... Because there's a lot of typing in the game". CJ commented they "would rather have a good audiogame" than a MUD. Marcela's and CJ's comments highlight some of the limitations of text-based interfaces: the need to learn specific commands to exercise control of the game, and players' preference for one form of control interface over another.

#### Gamers as creators

Some participants described engaging in the creation of games and game elements. For instance, Alberto said: "I'm part of a small team called Blind Gameplay, and we try to make our own versions of some games. I also do a bit of voice acting for some [audiogames]". CJ described their engagement on creative activities: "There was a time when I was trying to figure out how to make [3D binaural recordings]. I think it actually all started with... I was making some kind of audio scene and there was this part where I wound up kind of testing out some effects". Additionally, participants have explored the

use of tools for creating digital games. Carlos provided rich insights on the programming language *BGT*:

*"BGT was made by a dev called Philip Bennefall. It stands for Blastbay Game Toolkit. It's a language based on Angel script, which is not that hard to learn and there's a lot of blind people programming games with it. It's supposed to be only for games, but it uses a very old form of audio input, so you don't really have many options for this. You can only change the pitch and the volume and the patterning of the sound. You don't have any effects like HRTF<sup>1</sup> or anything."*

Carlos' description of his experience with *BGT* shows the potential role of GVI as game creators. Carlos finished by voicing his frustration around other game development tools and his aspirations for accessible game development tools:

*"I mean many people are now migrating to Python and C# and I guess that's good. Unity is not accessible though, otherwise people would probably use it... The only people who I know who code their audiogames in Unity are sighted people... If we had a language as powerful as Unity without the accessibility problems, we could have some really good games out there already."*

Our participants have shown they are involved in the creation of game elements through voice acting and sound recording. Moreover, at least one of our participants is well acquainted with the development tools used for the creation of audio-games and the limitations of mainstream game development platforms.

## DISCUSSION

Our qualitative analysis of these interviews with expert GVI has identified two key relationships between the gamers and the games they play: relationships with the information being presented, and relationships of control over the game world. These relationships occur both when the gamer is playing—or using—a game and when the gamer is engaged in activities of creation.

This analysis led us to develop the GIC (Gamer Information-Control) framework. The focus of the framework is the key relationships that allow GVI to access games, where the presence or absence of these relationships inherently enables or prevents GVIs' access to games. Relationships with information are supported by representations of space and of real-world objects, while relationships with elements of control are mediated through internal, in-game elements, such as text commands, and external elements such as screen-reading software.

### Relationships with information

Digital games convey navigational information for PVI through representations of the space and representations of objects from the physical world. These use metaphors from the physical world to communicate the affordances of the space

<sup>1</sup>HRTF: head-related transfer function; that is, a function describing how sound reaches the left and right ear at slightly different time intervals.

and the actions available to the player character within the game space.

### Conveying spatial information

Participants' visual impairment affects their relationship with physical space. As noted earlier, Juan summarised the perception of 3D space by most GVI in contrast to that of sighted players: *"we don't think that way, most of us"*. This aligns with the findings of Spiel et al. [75], Thinus and Gautnet [82], and Cattaneo et al. [24], who observed that PVI understand space differently than sighted players. Therefore, it is important for designers to consider how to best convey in-game spatial information.

Previous research has explored the relationship between space and sound in the context of embodied interactions [7, 89]. Our participants believe that combining binaural sound with head-tracking technology would result in an embodied interaction that would improve accessibility in digital games. Participants cited the *SeeMonkey* device as a promising technology for tracking the position of a player's head during the playing session, thus conveying information about space through a direct mapping of the physical and the virtual. Game designers may try embodied approaches to convey spatial information to GVI. This would improve the relationship between players and spatial information by more tightly coupling the two together, providing new signifiers to communicate positional information to all players (GVI or sighted).

Spatial information can be conveyed through other sensory inputs such as tactile or haptic [22, 64]. One of our participants noted the lack of additional sensory information. According to CJ, in digital games *"you don't have smell, or airflow, or anything like that"*. CJ's comments show a desire for additional channels of information. In previous research, haptic feedback has been used to assist people with visual impairment with mobility tasks in the physical world [3, 4, 17]. More recently, physical canes with haptic feedback to navigate virtual spaces have been designed [95], and cross disciplinary efforts have started exploring the use of scents to convey information [83]. There is an opportunity for game design to reduce overload on the auditory channel by considering other sensual input, such as haptic or olfactory feedback [15, 48, 51, 61]. This extended sensory engagement could enhance the player's sense of presence within the game.

Text is used to convey information to GVI, particularly in MUDs, where all the actions in the game are afforded through text commands. Our use of thematic analysis to "give voice to experience and meanings of the world, as reported in the data" [20], identified the importance and relevance of text-based interfaces for GVI. Carlos's opinion that text is a viable tool to convey spatial information that enables players to create a mental map of the game world to facilitate exploration, reflects this theme. While previous research on MUDs has focused on the types of players that engage with these games [11, 40] and the use of algorithms to automatically generate game layouts [39, 63], future research could explore the relationship between the use of spoken text and understanding of spatial information.



Marcela observed that so-called 3D audiogames really only allow for movement in four directions —up, down, left, and right. This restriction further constrains the relationship between GVI and in-game space. Works such as that of Andrade et al. [5] have explored the design of 3D virtual environments that give PVI freedom of movement and employ novel interaction metaphors such as echolocation to convey spatial information.

#### *Conveying information through objects*

Gaming is a deeply embodied experience in which the gamer is immersed in the game-world through the embodiment of a character [26, 46, 47]. GVI have even argued for the creation of sound-based character avatars [6]. This further justifies the use of extended sensory engagement to build a sense of embodiment and immersion in the game.

Just as the gamers themselves are embodied in-game through characters or avatars, objects and navigational tools may similarly be embodied, carrying and conveying metaphors and affordances from the physical world. Our participants described virtual representations of navigational tool objects such as radars or white canes. Other tools and objects such as footsteps and the echoes that result when those interact with walls are used in-game to convey information about the space. In the literature, radar and sonar-like systems have been used to indicate proximity to an object or person, for example, beeping more rapidly as the player walks towards a building [65]. These are examples of sound-based metaphors constructed around auditory icons that may be easier for PVI to associate with real-world phenomena than earcons [16, 31, 35].

Several of our participants use echolocation in the physical world, and one expressed an interest in using echolocation within the game environment as a further tool for exploring space. While previous research has established the usefulness of echolocation to identify size and materials of objects, and whether collisions are imminent in the physical world [27, 45, 50, 54, 78, 80], and exploratory research has identified echolocation as a potential metaphor to convey spatial information in digital games [5, 91], future research and game design could explore in depth the usefulness of echolocation as a metaphor to convey spatial information.

Voice is a non-physical element that is used to convey information. The spoken word is considered easier to process than earcons or auditory icons for conveying information [16, 70]. However, voice seems to be missing from the gaming experience of GVI. While the use of voice interactions in digital games has risen and fallen "in seven distinct phases in response to new platforms and enabling technologies" [1], none of our participants mentioned voice as a means for interacting with digital games, although Alberto does refer to the use of voice to communicate with other players through external software. Allison et al. [1] discuss the difficulties currently associated with voice recognition and interactions, which are frequently due to the limitations of available technology. This is in line with the findings of Sánchez, et al. [69], who assessed interaction trends in multimodal videogames for the cognition of people who are blind and found that only two out of twenty-five games assessed provided support for voice-driven interac-

tions. Game designers may integrate design patterns for voice interactions in order to improve how information is conveyed to GVI [2].

#### **Relationship with elements of control**

Control is obtained through internal and external elements. Screen readers are a prime example of external control provided to GVI, while the use of text commands and other interfaces enables internal control of a game.

##### *External control*

Participants expressed the need to be in control of the gaming experience, with CJ commenting *"If [a game] is going to lag or crash all the time on my system, that's going to be a problem"*, Carlos explaining how a particular screen reader "steals" the control of the keyboard and prevents gamers from playing certain games while the screen reader is on, and Alberto saying that he liked *"to have the screen reader on at all times"*. CJ, Carlos and Alberto's comments coincide with findings in the literature examining access to websites by screen-reader users [52, 92]. With screen readers being the main tool for PVI to work with computers [87], their desire to have the screen reader always on and not experience crashes is understandable. This study demonstrates how the GVI relationship to game interface controls differs from that of sighted players. Specifically, GVI control of screen readers should be privileged over other elements of control, because without this relationship, the GVI's gaming experience cannot start. Existing research has explored how screen-reader users recover from errors and crashes on the web [52, 86]. Handling of game crashes and compatibility with screen-reading software must be considered carefully by game designers creating games for PVI.

##### *Internal control*

A prominent feature of internal control is enabling interactions between gamers and the in-game character. All the gamers that we interviewed mediated these interactions using the keyboard. Juan, however, mentioned that certain games let him use the mouse to control the rotation of the character. This demonstrates that internal control of in-game elements is enacted through peripherals that are familiar to GVI, as keyboard and mouse are standard input devices that PVI use to interact with computers [69, 87]. Although some researchers have adapted mainstream console controllers for the use of GVI in experimental settings [25, 79, 89], the potential for these mainstream controllers to enrich GVI's gaming experience remains unexplored.

Control as a relationship goes beyond mediating interactions with in-game elements [87]. By internal control, we refer to the overall control gamers have over the gaming experience. Although all of our participants engaged with audiogames, some felt that MUDs offer more overall control over the gaming experience. As Carlos puts it, *"you can imagine what the world feels and looks and sounds like"*. By not relying on elements outside the control of GVI such as earcons, MUDs may deliver a deeper relationship to some GVI, as the gamers can imagine the entire world game. However, the use of text as a device to control in-game interactions may alienate other gamers, such as Marcela, who doesn't like *"dealing with the MUD client... because there's a lot of typing"*. Care should be

taken on how to integrate direct mechanisms of control such as text commands in a way that is appealing to GVI.

### Gamers as players and creators

The relationships with information and elements of control described above occur when the gamer is partaking in the gaming experience —while they are playing *or using*, their games. However, our participants have been involved in the creation of voice pieces for audiogames to convey in-game information, have explored how to record 3D spatialised sounds, and have tried tools such as *BGT* to create their own games: players are becoming co-creators [62]. These experiences reflect the creating relationships that need to be supported in order to enhance the gaming experience of GVI and that are routinely available to sighted players [9, 66].

Carlos reflected on the tools used for the creation of audio-games, concluding that *"If we had a language as powerful as Unity without the accessibility problems, we could have some really good games out there already."* There is at least one attempt that we are aware of to provide PVI the ability to create their own games, in the work of Stadler and Hlavacs [76]. Works like these enable an enhanced gaming experience, where gamers' lived experiences with disability is seen as a source of strength rather than as something that needs to be normalised [58, 67], and they are given means to explore different creative outlets. While our participants expressed their views on co-creating games, their views on ownership and creative processes have not been explored.

### FURTHER WORK

This paper has identified a number of opportunities to further explore the use and creation of digital games by PVI. We have described the use of metaphors to represent space and information within the game and to signify in-game affordances. To date, no work has focused on the interactions between PVI and game controllers. There is an opportunity to explore how PVI appropriate and customise game controllers as enablers of in-game control. Additionally, no work has to date focused exclusively on the experience of PVI as game designers.

We identify extended sensory stimuli as having the potential to convey additional information. The inclusion of these additional stimuli has potential to reduce load on the auditory channel and extend the player's sense of presence, immersion and embodiment within the game.

Although this paper examines key relationships, our framework focuses on the experience of individual GVIs. Research has yet to explicitly consider the relationships between GVI and other players, whether GVI or sighted, and the ways in which the combination of their abilities and unique skillsets can be exploited to create novel gaming experiences and interactions.

### CONCLUSIONS

In this paper, we have explored the understanding of the gaming experience of Gamers with Visual Impairment (GVI) focusing on the key relationships that enable GVI to interact with digital games. The relationship between GVI and information about the state of the game world is conveyed through

representations of space and representations of digital objects. The relationship between GVI and elements of control is mediated through internal game elements such as text, or external elements such as screen-reading software. Finally, these relationships with information and control elements occur both when the gamers are playing, or using, the games, and when they engage in creation activities.

The framework presented in this paper has provided a way of thinking about accessibility in digital games for PVI. We aim to encourage the design of games and game creation tools that are more accessible through the consideration of the elements outlined in our framework. This, in turn, will increase the capacity for people with different physical capabilities to fully engage with the gaming experience.

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## Chapter 5: A framework to understand accessibility in digital games

CHI 2020 Paper

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*2018 CHI Conference on Human Factors in Computing Systems (CHI '18)*. ACM, New York, NY, USA, Article 116, 14 pages. DOI : <http://dx.doi.org/10.1145/3173574.3173690>

## 5.5. Discussion

This chapter introduces the Gamer Information-Control (GIC) framework. The framework is one of few existing attempts to look at digital games for people with visual impairment without focusing on individual games as research artefacts (Wobbrock & Kientz, 2016), but instead finding common elements that make games accessible. These elements are not the result of a *post-mortem* analysis of existing games targeted at people with visual impairment, nor are they the result of theoretical assumptions made by the researcher. Instead, these elements are backed with empirical evidence and have been elicited via in-depth interviews with expert gamers with visual impairment. By working together with the gamers, this work advances a rhetoric of empowerment that recognises the unique skills of people with disabilities (Rogers & Marsden, 2013).

The framework identifies the importance of the relationships that exist between gamers and digital games, particularly regarding the way in which information is conveyed in-game. It also acknowledges the internal and external elements of control that govern interaction with games. Moreover, the framework recognises that these relationships exist both when the players engage with digital games as players and as creators.

Regarding how information is conveyed in-game, the framework identifies two key areas of particular interest to gamers with visual impairment: how spatial information is conveyed, and how information is conveyed through objects and phenomena. Previous research in the field of orientation and mobility has established that people with visual impairment use different mechanisms to form a representation of spatial information (Cattaneo et al., 2008; Thinus-Blanc & Gaunet, 1997). Therefore, it is critical to understand how this affects interaction with digital games. Importantly, the interviews

revealed that people with visual impairment are aware their spatial thinking may be different from that of their sighted counterparts, and that several “3D games” for people with visual impairment simply allow for the use of the four arrow keys—up, down, left, right—as opposed to just left and right. This is exactly what had been described by Ghali et al. (2012), who explain that games for people with visual impairment provide a grid-like system for participants to explore the game world. Although games that are widely played by people with visual impairment—such as *Swamp*—may follow this approach, the grid-like navigation pattern fails to deliver an experience that is equitably accessible, where people with visual impairment engage “in an ordinary way without getting special attention or being singled out” (van de Ven et al., 2005) and with the same degree of agency and efficiency as sighted players would do in modern mainstream games (Smith & Nayar, 2018).

The second aspect participants highlighted regarding how information is conveyed in games is the use of metaphors to represent real-world phenomena and objects. Of special interest for this thesis is participants’ description of how games have implemented echoes as signifiers of different elements—in some games, echoes are used to convey the presence of walls, in others, the presence of gaps. As a significant group of people with visual impairment use echolocation to acquire information about physical space (Thaler, 2013), defining a consistent approach to the use of echoes in digital games may provide an experience that is consistent. Moreover, this finding motivates further investigation on whether echolocation can be used in virtual worlds to facilitate learning about the layout of virtual spaces.

Regarding control, the interviews revealed that this is conveyed via elements that are both internal and external to the game. Screen-reading software is a clear example of

an external element that mediates control—without the screen-reading software the player may be unable to initiate the gaming session. In-game commands, be they literal text commands or just key presses, constitute an example of internal control elements. Existing games mediate control through the use of a keyboard, although previous research has described the use of mainstream game controllers—Wii remote and Xbox controller—in gaming experiences targeted to people with visual impairment. Examples include Cheiran et al. (2011), Swaminathan et al. (2018) and Wilkerson et al. (2010). Moreover, some participants from study 1 had tested experimental hardware to provide head-tracking capabilities and overall liked the feedback provided by such hardware. A final consideration to be made about control is that it moves dynamically, as gaming sessions demand gamers to interact with several systems simultaneously: screen-reading software, video conferencing software, the game itself, internet forums, et cetera. Similar findings have been made in the context of the workplace, where different people with visual impairment adopt different configurations for their assistive technology, and use them in different modes to support their work (Wahidin et al., 2018).

Finally, the framework recognises the role of gamers as creators of both information and control elements. The interviews revealed that gamers with visual impairment are involved in the development of games to different degrees, including voice acting for some games, creation of 3D binaural recordings, and even attempts at creating their own games from scratch. Participants acknowledged existing limitations when trying to use industry-standard game development tools and argued for the need for more accessible creation tools.

The paper presented in this chapter describes a series of elements that game designers should take into account when analysing accessibility of digital games for

people with visual impairment. In relation to this thesis, the interviews with participants and the development of the Gamer Information-Control framework highlight the importance of conveying spatial information, and hint at the potential of metaphors that simulate real-life phenomena, such as echolocation, as an interesting avenue for exploration. Together with chapter four, section II of this thesis provides a unique in-depth picture of gamers with visual impairment, and fosters a discourse of empowerment by giving voice to an underrepresented group (Mankoff et al., 2010).

Upon completing study one, described across chapters four and five, the main research question for this thesis was refined and became: *how can echolocation be designed as a means for people with visual impairment to acquire spatial knowledge of digital space?* as presented in chapter one. This question did not emerge from a theoretical conjecture posed by the researcher, but rather, it is based on a deep understanding of the experience of gamers with visual impairment. Moreover, this question responds to the findings presented in the GIC framework: that spatial information is key for accessibility in digital games. Additionally, this question explores the usefulness of a novel metaphor to acquire this information. The following section provides an exploration of this question through a series of user studies in laboratory settings.



## Section III:

# Implementation



# Chapter 6: Echolocation in Virtual Worlds: A Feasibility Study

## 6.1. Introduction

Section I provided a theoretical foundation for this thesis, exploring previous works in the fields of accessibility in digital games for people with visual impairment, echolocation, and spatial information acquisition. Section I also described the critical-realist lens that underpins the research presented in this thesis. Section II investigated the practices of gamers with visual impairment and introduced the Gamer Information-Control (GIC) Framework. The GIC framework illustrated the importance of conveying spatial information to improve accessibility in games. Furthermore, the GIC framework presented a series of metaphors based on real-world phenomena that are used to improve accessibility in digital games. Of particular interest for this thesis is the potential of echolocation as an in-game metaphor to convey information.

This chapter presents the results from Study 2A and answers **RQ2**: how can echolocation be implemented in virtual worlds so that it supports acquisition of spatial knowledge? Although there have been previous attempts at creating echolocation-enabled virtual environments, these implementations tried to replicate echolocation as realistically as possible (Pelegrin Garcia et al., 2014; Picinali et al., 2014; Robinson & Kearney, 2016).

However, these realistic implementations are computationally expensive and require the use of specialised equipment usually unavailable outside the laboratory. Other implementations consisted of proofs-of-concept and have not explored how echolocation could support acquisition of spatial knowledge (Ramos & Arias, 1997), or provided a grid-like navigation system that limits players' ability to move freely in a virtual world (Wu et al., 2017). The implementation presented in this chapter is different because it: a) provides a virtual environment that is not designed following a grid-like navigation system. This is done in an attempt to deliver an equitably accessible experience; b) uses inexpensive, off-the-shelf components; and c) explores the feasibility of using echolocation to learn spatial information in virtual worlds. These differences reflect the critical realist lens that is applied to this thesis. They respond to the needs identified by people with visual impairment themselves and allow for the production of knowledge that can be built on by others exploring the relationship between technology and disability.

This chapter presents the results from a laboratory-based evaluation of an echolocation-enabled virtual environment with a small group of people with visual impairment. The evaluation revealed that: a) it is possible to create echolocation-enabled virtual environments using off-the-shelf components; b) the implementation of echolocation presented in this paper enabled participants to identify several spatial features, suggesting that echolocation may indeed be useful to learn about spatial information in virtual space; c) echolocation seems to enhance the sense of presence in virtual worlds; and d) it is necessary to provide scaffolding mechanisms and additional orientation cues for participants to successfully learn to interpret the echolocation feedback.

The results described above were reported in a paper entitled: “Echo-House: Exploring a Virtual Environment by Using Echolocation”. The paper was accepted for publication in the proceedings of *the 30<sup>th</sup> Australian Conference on Computer-Human Interaction (OzCHI’18)*. The paper was reviewed by two anonymous reviewers and a meta-reviewer. Similar to previous publications in this thesis, the paper appears “as is”, following the formatting of the publisher. References of the paper are presented at the end of the paper instead of in the References section of this thesis. This paper demonstrates that it is possible to implement an echolocation-enabled virtual environment using existing off-the shelf components.

### **6.2. How this paper contributes to the thesis**

This paper constitutes a proof-of-concept feasibility study that demonstrates how to implement echolocation in virtual worlds. This is an initial step in using echolocation in virtual worlds to acquire spatial information. This paper complements the findings from the GIC framework (chapter five) regarding the use of metaphors to convey spatial information to improve accessibility in digital games for people with visual impairment. Furthermore, this paper implements echolocation as a metaphor to facilitate exploration of virtual spaces using off the shelf components.

### **6.3. Data collection and analysis methods**

The paper presented in this chapter describes Study 2A: an experimental laboratory-based evaluation followed by semi-structured interviews. This study uses a mixed-methods approach to explore the feasibility of implementing echolocation in virtual worlds so that

it supports acquisition of spatial knowledge, and follows an explanatory sequential design (Creswell & Plano Clark, 2011, pp. 53-106). According to this experimental design, a quantitative data collection and analysis phase is followed by a qualitative phase. The goal of the quantitative phase is to provide an initial overview of a phenomenon, and the aim of the qualitative phase is to further explain the quantitative results. The quantitative data collection occurred automatically during the experimental phase, in which participants had to interact with an echolocation-enabled virtual environment. The qualitative data collection was conducted via semi-structured interviews after the experimental phase.

The two key quantitative variables measured during the experimental phase were: completion times, and number of times participants used different auditory stimuli provided in the environment. The auditory stimuli included: footsteps that were played automatically as participants moved a virtual avatar, artificially synthesised mouth-click sounds created from samples taken from expert echolocators (Thaler et al., 2017), and pre-recorded clapping sounds. These three sounds were chosen because they are some of the most common sounds echolocators use (Stroffregen & Pittenger, 1995; Thaler, 2013).

Completion time and number of times participants used the available auditory stimuli were analysed using descriptive statistical measures, such as frequencies and means. The goal of measuring completion times was to establish if it was possible at all for people with visual impairment to complete a navigation task in a virtual environment. Measuring the number of times participants used the auditory stimuli provided, supports the claim that participants could complete navigation tasks in virtual worlds *because of* their use of echolocation.

The follow-up semi-structured interviews focused on exploring participants' opinions about the experience of completing a navigation task in a virtual environment while being supported by echolocation. Qualitative data were analysed using thematic analysis (Braun & Clarke, 2012). This analysis focused on participants' opinions about the implementation of echolocation in the virtual world, the way in which the virtual character they controlled moved around and interacted with the virtual world, and the perceived need for additional support to learn how to use echolocation in a virtual world more successfully. Two participants were expert echolocators and they also provided feedback on how the current implementation of echolocation compared to their own echolocation capabilities in the physical world.

### **6.4. The paper**

A PDF file of the paper can be found at <http://go.unimelb.edu.au/zd9j>.

## Echo-House: Exploring a Virtual Environment by Using Echolocation

Ronny Andrade, Steven Baker, Jenny Waycott, Frank Vetere

School of Computing and Information Systems - The University of Melbourne  
Melbourne, VIC, Australia

{andrader, steven.baker, jwaycott, f.vetere}@unimelb.edu.au

### ABSTRACT

The graphics-intensive nature of most virtual environments (VEs) prevents many people with visual impairment from being able to successfully explore them. A percentage of the population of people with visual impairment are known to use echolocation — sound waves and their reflections— to better explore their surroundings. In this paper, we describe the development of an echolocation-enabled VE (Echo-House) and evaluate the feasibility of using echolocation as a novel technique to explore this environment. Results showed that echolocation gave participants an improved sense of space in the VE. However, the evaluation also identified a range of orientation and mobility issues and found that participants needed additional support to gain confidence in their use of echolocation in the VE. Our findings suggest that with proper support, echolocation has the potential to improve access to VEs for people who are blind or visually impaired by revealing features that would be otherwise inaccessible.

### CCS CONCEPTS

- Human-centered computing~Auditory feedback
- Human-centered computing~Accessibility systems and tools

### KEYWORDS

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Visual impairment, echolocation, virtual environments, exploration; games; accessibility.

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### 1 INTRODUCTION

Technology has facilitated access to information and generated new possibilities for entertainment. Virtual experiences, such as virtual environments (VEs) and videogames, and their ever-increasing relevance in popular culture are a prime example of this [9, 18]. However, the high sensory capabilities that most virtual experiences require from their users leads to the exclusion of users with different physical or mental abilities. In the case of people with visual impairment, exclusion from virtual experiences is most evident, as they cannot rely on the visual output that most of these experiences produce.

People with visual impairment need to use nonvisual stimuli to construct a mental map of their surroundings, both in the physical and virtual world [34]. Despite the development of different approaches to navigation of virtual spaces, there are unexplored opportunities to incorporate navigation techniques that people with visual impairment use in the physical world into VEs.

In this paper, we aim to explore the feasibility of building a VE that allows for the simulation of echolocation —the use of sound waves and their echo reverberations — and evaluate the use of echolocation as a novel technique to assist people with visual impairment to explore the environment. To do this, we present a prototype echolocation-enabled VE, Echo-House, and discuss findings from a small-scale proof-of-concept laboratory-based evaluation conducted with participants who have a range of visual impairments. While we have focused on the development of a VE, the



overlap between VEs and videogames means that our findings could equally be applied to existing videogames or used to create new and more accessible games.

We begin by introducing the concept of sensory substitution, which underpins the way in which people with visual impairment interact with technology. This will be followed by a review of previous work on echolocation and a review of the existing trends in virtual experiences for people with visual impairment, focusing on videogames. We then describe the design decisions made in implementing the prototype of Echo-House and the methodology followed for its evaluation. Finally, results from the prototype evaluation are presented, and we discuss conclusions regarding the feasibility of using echolocation as a novel technique to explore VEs.

### 1.1 Sensory substitution

In order for people with visual impairment to navigate the world around them, it is necessary for them to use mechanisms that replace visual sensory input with other types of input. Sensory substitution is the translation of information from one sense to another, with auditory and tactile feedback being the most common senses used to replace visual feedback [26]. Research in this field is extensive, with Bach-y-Rita et al. [6] studying this field for decades, and trialing systems that use other sensory organs, such as the tongue [2, 5, 23], or the skin [3, 4] to replace visual information.

Specific sensory-substitution devices, that aim to assist people with visual impairment to navigate the physical world by replacing visual feedback with tactile or auditory feedback, have appeared in the literature: [6, 17, 24, 26]. These devices use cameras, ultrasound or optic emitters paired with a receiver to detect deflections of emitted signals. Once a signal is emitted and detected by the receiver, these devices produce either auditory or tactile feedback to indicate characteristics of the environment, such as distance between the user of the device and potential obstacles. 3D printed tangible interfaces have also been explored as means of sensory substitution to assist people with visual impairment to create a mental map of their surroundings [21, 36, 37].

The sensory-substitution approach has been taken to virtual worlds primarily by using auditory cues as substitutes for visual cues: Ohuchi et al. [29] presented a sound-based virtual maze that participants could explore with a game controller instead of by walking, in order to form a mental map of a location. Sánchez et al. [35] and Connors et al. [15] describe the design, implementation and evaluation of a VE that was modelled after a location in the real world. Players with

visual impairment could explore the VE via the use of sound cues. Ohuchi et al. [29] and Connors et al. [15] agree that using sound-based virtual mazes modelled after locations in the real world improves the capabilities of people with visual impairment to create a mental map of an unknown location.

### 1.2 Echolocation

Echolocation is a skill that has been observed in bats and some aquatic mammals [40]. According to Kolarik et al. [24], and Kupers et al. [25], echolocation in humans is the ability to use self-generated sounds and their echo reverberations to build a mental image of the surrounding spaces. The sound can be generated through a mouth-click, a clap, footsteps, or by hitting a cane on the floor. The use of self-generated sounds and echoes stimulate the visual cortex of the brain of echolocators [24, 39], resulting in a form of sensory substitution by which visual input is replaced by auditory input.

The process of echolocation consists of two steps: transmission, which is the process of producing a sound, usually with the mouth, and reception, which is the process of listening to the sound emitted as it combines with its reverberation over surfaces. Over long distances, there is a perceptible gap between the moment the person listens to the sound they have produced and the upcoming echoes [24, 40].

Most individuals who echolocate use clicking sounds produced with their tongues [32]. The physical characteristics of the clicking sounds echolocators use have been analyzed. Kolarik et al. [24] and Thaler et al. [40] have found that the mouth-clicks produced by individuals who echolocate last for approximately 3ms to 10ms, with an interval of 250ms between clicks. Sound levels range from 60 to 108 dB SPL, with maximum energy in the frequency range of 8 kHz to 10kHz. Thaler et al. [40] have produced artificial clicks based on the parameters obtained from gathering a large sample of mouth-clicks produced by expert echolocators as a step towards the development of computational models of human echolocation.

It is estimated that 20 per cent to 30 per cent of blind individuals can use echolocation in varying degrees [38], and the functional benefits that echolocation offers include: the ability to determine distance, position, size, shape or material of surfaces or objects by detecting sound reflections over them [24, 38, 39]. These benefits highlight the potential for echolocation to provide a more nuanced form of sensory substitution in VEs when compared to existing auditory-cue-based approaches. Moreover, according to Thaler [38], previous research has found that echolocation improves spatial

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orientation skills in blind people under experimental conditions.

Some of the obstacles in learning echolocation are the amount of practice it requires, the cognitive load it creates and the fact that training methods are still in the early stages of development [30]. An initial attempt to teach echolocation by using technology is presented by Wu et al. [44], who have developed a mobile application that uses pre-recorded echoes to provide orientation and navigation clues for users exploring a grid-like maze environment. Based on a preliminary evaluation of this system, Wu et al. concluded that using echoes in a virtual maze could be a promising way of increasing people's awareness of echo cues. However, that research is still in development and, to the best of our knowledge, this is the only study to date that explores the potential use of echolocation in a VE. Notably, the aim of Wu et al.'s research is to train people to use echolocation, rather than using echolocation as a way of enabling visually impaired people to explore VEs.

In the following section, we explore the various existing approaches that have been taken to attempt to make virtual experiences, particularly videogames, more accessible to visually impaired or blind users. This is crucial, as people with low or no vision rely on the combination of different mechanisms, such as canes, guide dogs and echolocation, to make sense of their surroundings, it is likely that a range of approaches will be needed to navigate VEs.

### 1.3 Virtual experiences for visually impaired people

Virtual experiences occur outside the physical world and include virtual environments and videogames. There is an overlap between VEs and videogames; however, a videogame is usually contained within a VE, and a VE may or may not involve game play [9]. There is a growing body of literature that describes virtual experiences designed for people with visual impairment. [15, 20, 26, 29, 34, 41], where the terms "virtual environment" or "videogame" are used interchangeably. These experiences use sensory substitution as their basis for interaction by replacing visual with auditory output and the goal of some of these experiences is to assist people with visual impairment in the creation of a mental map of specific locations [15, 29, 34].

Without sensory substitution, VEs remain barely accessible to blind and visually impaired people [27]. However, a new trend in accessible videogames is emerging: audiogames. These are "computer games that feature complete auditory interfaces, so that they can be played without the use of graphics" [19]. A collection of

over 700 of these games can be found on the website <http://www.audiogames.net>. The site offers games of different genres and hosts a thriving community of game developers and players with visual impairment.

Interaction in audiogames is based on earcons, and voice cues. Earcons are auditory representations of messages, functions, states and labels used in computer systems—and, by extension, in computer games—as alternatives to visual icons [10]. Blattner et al have categorized earcons as representational earcons, also known as auditory icons, and abstract earcons [10]. Representational icons are digitalized versions of naturally-occurring sounds, and abstract earcons are earcons constructed using a single pitch or a group of pitches.

According to White et al. [43], unlike videogames, audiogames lack a consistent set of earcons to convey cues from the game. This lack of consistency means that each new audiogame experience must be learned afresh. Audiogames aim to provide players with visual impairment with mechanisms to focus on exploration as a central part of the gaming experience, making navigation itself a "fun and open-ended part of the experience" [19], even if each new audiogame requires for the player to become familiar with a new set of earcons.

While audiogames can encourage exploration, the current interaction mechanisms limit the degree of freedom that players have for exploring. Ghali et al. [20] have found audiogames rely on the following three interaction patterns: verbal information, where the players are told when to press a key to produce an action; time-based mechanisms, where actions of players are timed by earcons; and constrained navigation mechanisms, where the player usually moves over a grid, with one press of a key corresponding exactly to one step, and movement occurring over a predefined set of positions and in four specific directions: up, down, left and right.

We propose the use of echolocation as a way to assist people with visual impairment in freely exploring VEs using a novel technique that provides a greater degree of freedom than the techniques currently used in audiogames. To achieve this goal, we have designed and evaluated Echo-House, a VE that supports the use of artificial mouth-clicks, claps and echo reverberations, enabling for the simulation of echolocation.

## 2: DESIGNING ECHO-HOUSE

Echo-House is the echolocation-enabled virtual environment (VE) designed for this study. It was created using Unity 5.6 and the echolocation features

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were developed with the SteamAudio plug-in, version 2.0 beta 5. Echo-House consisted of three levels with different layouts, as shown in Fig. 1 (not drawn to scale).



Fig. 1: Layouts of the three levels created as part of Echo-House.

### 2.1 Layout of Echo-House

The three levels of Echo-House were modelled after rooms in a house. Each level had a goal that participants needed to reach in order to move on to the next level (marked as an X on the layouts presented in Fig. 1). Level (a) represented a long corridor with two tall drawers as obstacles; level (b) was modelled after a bedroom with pieces of furniture around the room, and level (c) was modelled as a living-room with a TV set, a couch, cabinets and a u-shaped inner wall. The use of Unity and the SteamAudio plug-in allowed for the generation of 3D binaural sounds to indicate the position of the goals in each level, creating a sense that each goal had a fixed position in space. Each goal had a unique representational earcon associated with it. The earcon chosen for level (a) was the sound of a cat meowing; in level (b) participants could hear an alarm clock; and in level (c), the sound of candy being unwrapped indicated the position of the goal.

While we used 3D binaural sound to signal the goals of each one of the three levels, each level presented a unique experimental condition (described further in the Methodology section below). Level (a) allowed participants to use echolocation but did not give any feedback if they hit an obstacle, level (b) used voice cues indicating the name of the object participants collided with but did not provide echolocation support, and level (c) used both echolocation and voice cues with the name of the objects participants collided with. Table 1 summarizes the layout, auditory icon to indicate the goal, and experimental condition of each level.

Table 1: Summary of the three levels of Echo-House, their layout, auditory icon to indicate the location of the goal, and experimental condition

| Level | Layout      | Goal cue | Condition                   |
|-------|-------------|----------|-----------------------------|
| (a)   | Corridor    | Cat      | Echolocation only           |
| (b)   | Bedroom     | Alarm    | Voice cues only             |
| (c)   | Living room | Candy    | Echolocation and voice cues |

### 2.2 Exploring Echo-House

To explore each level of Echo-House, participants controlled a virtual avatar created from the Unity standard assets. To increase the feeling of presence in the VE, the virtual character could use one of these three auditory icons: footsteps, artificially synthesised mouth-clicks or claps. The three sounds could be produced in all levels; however, the sounds did not produce any echo on level (b). The footsteps were heard automatically as participants walked around Echo-House, whereas participants were able to control when to produce the mouth-click sound or the clapping sound by pressing the space bar or the Control key. Additionally, participants could use the Alt key to hear the 3D binaural cue that indicated the position of the goal. The character used in this study could move like most characters in first-person games: the arrow keys controlled the direction in which the character moved, and the keys a-w-s-d controlled the position of the camera that indicated the avatar's first-person perspective.

### 2.3 Echo capabilities in Echo-House

By using Unity and the SteamAudio plug-in, we were able to generate real-time physics-based sound reflections based on the geometry of each level. The sound reflections generated by the plug-in used a head-related transfer function (HRTF) to simulate how sound reaches a listener, and the delay produced when the sound reaches each ear. This delay is a key factor for echolocators to estimate distance of surrounding objects or obstacles [44] and through the simulation of the sound reflections and HRTF we gave Echo-House echolocation capabilities.

It must be noted, however, that Echo-House used a generic HRTF provided by the SteamAudio plug-in. While a customized HRTF could have improved participants' sense of presence, person-specific HRTFs are time-consuming to build [33], and the version of the plug-in used in Echo-House does not accept customized HRTFs.

Another feature of the SteamAudio plug-in is the ability to assign materials such as wood, ceramic or



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carpet to each element —wall, floor or piece of furniture— in Echo-House. Objects modelled with different materials absorb and reflect sound frequencies differently [24, 45]. This difference in sound reflection based on materials produced a more realistic experience, particularly for participants who know how to use echolocation in the physical world.

The artificial mouth-click the virtual avatar emitted was modelled upon the data and model proposed by Thaler et al. [40], which was based on a large number of samples collected from three expert echolocators. With the samples, Thaler et al. were able to produce a model of synthesized mouth-clicks optimized according to the parameters obtained from the three expert echolocators.

### 2.4 Additional considerations

Apart from the echolocation capabilities, Echo-House incorporated voice cues and representational earcons. At the beginning of each level, participants would hear a brief description of the room they were in and the goal they had to reach. We chose to use pre-recorded voice cues over artificial speech synthesis and representational earcons over abstract earcons in an attempt to create an interface that is more appealing for participants [34].

While Wu et al. [44] proposed a system that enabled the use of echolocation to explore a virtual space, there are significant differences between their implementation and the one presented in this study. In particular, Wu et al. aimed to facilitate the learning of echolocation whereas we are evaluating if it is feasible to explore a virtual space using echolocation as an interaction technique. These different goals resulted in different ways to move around the virtual space. While Wu et al. used a grid-like system, we gave players the ability to move in any direction and for any length they desired. Moreover, our approach to producing echoes is different. Wu et al. relied on pre-recorded echoes, while we produced real-time echoes based on the geometry of the virtual room.

## 3 METHODOLOGY

To assess whether echolocation can feasibly be used to explore a VE, we conducted a pilot evaluation study of Echo-House. In addition, we aimed to gain in-depth insights about participants' experiences of using echolocation in a VE. The study required participants to use the Echo-House VE for a pre-determined period of time and then participate in a semi-structured interview. Quantitative and qualitative methods were used to analyse data gathered from five participants.

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This project received approval from the Ethics Committee of the University (Ethics ID 1749810).

### 3.1 Participants

Participants were recruited via posts on online noticeboards, the University Student Equity and Disability Services, and word-of-mouth. Five participants were recruited for the study. They will be referred to as P1-P5 in this paper. Our decision to not engage with the community of visually impaired people outside of the university for this proof-of-concept evaluation made it difficult for us to obtain a larger sample. All participants self-identified as visually impaired. Table 2 summarizes the characteristics of the participants.

**Table 2: Characteristics of participants, including their age range, impairment, whether they know how to echolocate and the assistive technology they used**

|   | Age range | Impairment                  | Echolocator | Assistive technology |
|---|-----------|-----------------------------|-------------|----------------------|
| 1 | 50-60     | Low vision                  | No          | None                 |
| 2 | 20-30     | Blind                       | Yes         | Screen reader        |
| 3 | 50-60     | Blind                       | Yes         | Screen reader        |
| 4 | 20-30     | Low vision                  | No          | None                 |
| 5 | 70-80     | Low vision, hard of hearing | No          | Magnifier            |

For this study, a decision was made not to use sighted blindfolded control subjects. While this had consequences in relation to the number of participants that could be recruited, previous studies that have compared the echolocation capabilities in blind and sighted participants have found that, on average, blind participants outperform sighted counterparts [25]. Moreover, people with low or no vision have learned a set of orientation and mobility techniques that sighted counterparts have not developed, as the latter rely almost entirely on their sight to navigate new spaces [31].

### 3.2 Procedure and data collection

The study consisted of a 45-minute playing session and a 15-minute semi-structured interview. While the interview was scheduled to last 15 minutes, P2, P3 and P5 were happy to go beyond the pre-established time. This commitment allowed them to provide additional

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rich insights on their interaction with Echo-House. During the playing session, participants had to explore the three levels of Echo-House described in Fig. 1 and were encouraged to think aloud to describe what was going on in their heads during the playing session. Think aloud data were included in the qualitative analysis.

This study followed an alternating treatments design [7] to ensure that the order in which participants explored the levels of Echo-House did not affect the final results. Participants were separated in two groups. One group completed the levels in the following order: (a), (b), (c), the other group completed the levels in following order: (c), (a), (b). To prevent carryover effects, or the effects of participants reaching the goal quicker after becoming familiar with the layout, each level had a different layout, as shown in Fig. 1. As already discussed and shown in Table 1 each level had a different experimental condition, with level (a) having echolocation-only, level (b) having voice cues only, and level (c) having echolocation and voice cues. The condition of no echolocation was introduced as a control, while the combined echolocation and voice cue condition allowed us to consider the impact that combining modalities would have on the participants ability to navigate the environment, as compared to echolocation only.

Qualitative and quantitative data were gathered to evaluate the use of echolocation to explore the VE. The participants' playing session was automatically recorded. Video and key logs were generated. Upon completing the playing session, participants took part in a semi-structured interview. If participants knew how to echolocate in the physical world, they were asked a set of slightly different questions that focused on understanding this skill and how they correlated it to the VE. The interviews were audio-recorded after obtaining participants' consent.

Quantitative data obtained from the video recordings of participants' playing session and log files were analyzed using descriptive statistics graphics. The data obtained from the think aloud process and the interviews were analyzed using thematic analysis [1], where the analysis focused on identifying themes related to participants' ability to explore the VE.

### 3.3 Physical set up

Fig. 2 shows the setup used during the evaluation. Participants sat in front of a monitor, a mouse and a standard English-layout keyboard. The monitor and the mouse were not connected to a computer but were there to act as props and emulate a gaming desktop PC. The keyboard was connected to a laptop that ran Echo-

House. The laptop was positioned so that even if participants had low vision they could not look at the screen.

Participants used semi-closed headphones during the gameplay. This type of headphone partially isolates external noises. The pair of headphones used during gameplay provided a flat frequency response, without creating the bass enhancement which is common in most commercial headphones. The echo produced by the elements in the VE was amplified so that it would be easier for participants to detect it.



Fig. 2: Participant interacting with Echo-House

All participants agreed to feeling comfortable and familiar with the use of a standard computer keyboard. Moreover, Sánchez et al. [34] have found the keyboard to be the most common input device used in games for people with visual impairment.

## 4: RESULTS

In this section, we describe quantitative and qualitative results from the evaluation of Echo-House. Quantitative results include the time participants took to complete each level, and the number of times participants used the different audio cues provided in Echo-House. Qualitative findings center around how echolocation in the VE compares to echolocation in the physical world, participants' opinions on the way they interacted with Echo-House, and participants' need for proper scaffolding in order to take the most advantage of echolocation in Echo-House.

### 4.1 Quantitative Results

Descriptive statistical analyses of the auto-recorded videos of participant playing session and log data focused on two key aspects: completion time of each level, and number of times participants used the different audio cues available: artificial mouth-clicks, claps, or a 3D binaural sound to indicate the position of the goal. Table 3 shows completion time for each level, and Fig. 3 shows the use of the sound cues.

Table 3 shows that all participants except P2 took less than 30 minutes to complete the three levels of

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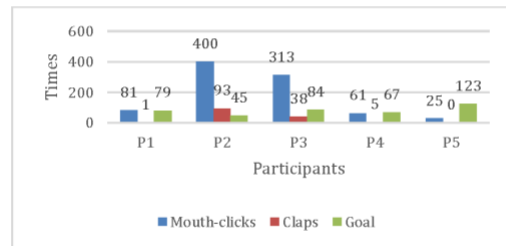
Echo-House. The table also shows P2 and P3 took the longest to complete level (a). This level offered the echolocation-only experimental condition, so P2 and P3 spent several minutes familiarizing themselves with the artificial mouth-click, the clapping sound, and the echo these sounds produced. Finally, the table shows that all participants, except P2 completed level (b) faster than the other levels; level (b) was the voice-cues only control condition.

**Table 3: Completion time by level and participant in minutes and seconds**

| Participant | Level (a) | Level (b) | Level (c) | Total |
|-------------|-----------|-----------|-----------|-------|
| 1           | 6:25      | 4:09      | 17:56     | 20:30 |
| 2           | 10:24     | 14:48     | 22:46     | 47:58 |
| 3           | 17:30     | 3:04      | 9:07      | 29:41 |
| 4           | 6:40      | 5:02      | 8:33      | 22:15 |
| 5           | 6:59      | 4:36      | 9:43      | 21:18 |

Fig. 3 shows the total number of times participants used the sound cues available to them: artificial mouth clicks, clapping sounds, or a 3D binaural sound indicating the position of the goal in the virtual space. The Fig. shows that participants who were blind (P2 and P3) generated many more mouth-click and clapping sounds relative to the participants with low vision. This predisposition to use the echolocation cues could be attributed to the fact that P2 and P3 have used echolocation for years. The Fig. shows that P2, who used the mouth-click and clapping sounds the most, was also the one who used the 3D binaural cue that indicated the position of the goal less often, while P5, who was hard of hearing, relied almost entirely on the 3D binaural cue that indicated the position of the goal. This suggests that participants each had their own preferences for how to navigate through the levels, with the two participants who already used echolocation using the echo cues more often than the other participants. It was to be expected that P5 preferred not to use the echolocation cues, as this participant was hard of hearing; however, P5 could successfully perceive the binaural 3D sound that signaled the position of the goal.

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**Fig. 3: Total number of times participants used the artificial mouth-clicks, the clapping sounds, or the 3D binaural cues indicating the position of the goal**

#### 4.2 Qualitative Results

The following sub-sections describe the common themes found across the interviews with the different participants. These themes include: echolocation in the VE and how it compares to echolocation in the physical world; comments on movement and interaction; and the need for additional support, or scaffolding, to successfully use echolocation in a VE.

**4.2.1 Echolocation in the virtual environment.** All participants except P5, who is hard of hearing, were able to perceive the echo generated in the VE after emitting the mouth-click or clapping sounds in the levels that supported it. The echo was described by the participants as giving them a sense of space. While exploring level (a), which simulated a long corridor and where echolocation was the only feedback available, P3 stated “The room seems very deep with the [mouth] click”, and as soon as P3 reached level (c), which simulated a living-room and provided echolocation and voice cues support, they said “Bigger... much more echo here”. Similarly, when reflecting on the experience, P4 said “the echo gave me a sense of space, but I found it hard to work out how far away I was. I think sometimes it was louder than others”.

Regarding spatial navigation of the VE, P1 said “by the amount of walking I had to do, [level (a)] felt like a long corridor”. Once again, this participant’s perception of the environment matches the actual layout. Moreover, the gameplay think aloud comments of P2 and P3 showed them successfully identifying walls and drawers in different levels of Echo-House. For example, P2 said: “it looks like there’s something up to the right” when exploring level (a) with the artificial mouth-click and standing next to a wall on their right.

Participants commented on the need to learn to understand the sound emitted and the echo received. P1 said: “I didn’t know how to interpret the different sounds to find my way out”. This is true for participants



who can echolocate as well; after finishing the evaluation of Echo-House, P3 declared: “I was probably learning what that click sounded like and of course that was going to take some time”. This shows that participants needed time to become familiar with the echo produced in the VE.

Echolocation works differently for each person because of the uniqueness of the mouth-click and HRTF of each individual [32, 33]. This was evident when P2 and P3, both expert echolocators, interacted with Echo-House. For P3, the artificial mouth-click used in the VE was less sharp than his own: “The click sound isn't as sharp as the one that I usually make myself [even though] I'm not sure if my click is unusually sharp”, they said.

Participants also obtained different degrees of spatial information from the sounds available. P3 declared “I get more information from the clap rather than the click, which is unusual. I get more information usually from the click myself”, while the opposite was true for P2.

People who use echolocation make sense of their surroundings by listening to the delay of the echo coming back to their left and right ears. P2 and P3 felt this delay, especially on level (c), which simulated a spacious living-room, with P3 saying “[this level] probably feels bigger so I'm hearing more of the sound delay”, and P2 saying: “on the left is more delayed that's how you can tell there's more space on the left”, while standing on the bottom right corner of level (c). However, regarding the accuracy of the delay, P2 added: “I think maybe the simulator is too quick with the feedback because it's all about the time; the timing of the feedback indicates what the distance is and it's such a small change... it's just happening so quickly. I really have to be listening for it”.

Our analysis suggests that while participants successfully perceived the echoes generated and could get some idea of the VE, the echolocation accomplished with Echo-House did not necessarily feel like the echolocation they were used to from their experience in the physical world. P3 said: “So normally as I move closer to a wall I would hear it more clearly than I'm hearing it here”. When asked whether using echolocation in the virtual world would affect their echolocation skills in the physical world, P3 said it would not.

**4.2.2 Moving and interacting.** Participants pointed out the need for more information from the environment and the way in which the virtual character interacted with it. When colliding with obstacles on level (a) (corridor, echolocation only), P1 wondered: “Am I walking past cabinets or getting into the cabinets? I

didn't know if I was walking past [the cabinets] or actually banging into them”. Regarding how the virtual avatar interacted with the environment, this participant declared: “I didn't know how tall things were or if I was just walking past them or if I could climb over them or if I had to go all the way around them”.

P1, P2 and P5 pointed out other physical differences they felt when exploring Echo-House when compared to the physical world. P1 mentioned the ability to hear a sound to indicate where the goal was: “the ability to make the target make some sound, I don't think you could necessarily count on that in real life but it's good that you could do that in the virtual environment”. P2 highlighted the lack of the physical feeling of the room: “if I walk into this [lab] room, I can tell there's concrete under the carpet, the carpet is not a fancy carpet that feels good to walk on, and that [feeling] was not at all on the computer”. P5 explained how they get information from the world via the sense of touch: “I use the balls of my feet to feel the rough things on the edges of the train platform [and] not get lost when I walk from one platform to another. I use the walking stick to prep where steps are, where the edges are. It is a very tactile thing and I was missing this feedback in the game”. This matches previous findings regarding the sense of presence in VEs [33, 42].

Regarding using the arrow keys to move the virtual avatar around the environment, P2 initially expressed concerns about not having a frame of reference for how each key press mapped to the virtual avatar. The virtual avatar required longer presses to walk and P2 was pressing the arrow keys softly for very brief intervals. After a while, the participant figured out for how long to press the keys and declared “It took me a while to get used to them... and then I went into this sort of more explorative mode”. This is visible in the auto-generated video recordings of P2 playing session, where at first, they moved very slowly and after discovering how the key-press affected the movement of the virtual avatar, they started moving more swiftly. While P3 did not comment on the effect of the key-press in the movement of the virtual avatar during the post-interview, video analysis of their playing session revealed a similar behavior, starting with short arrow key presses then using longer key presses as they understood how much it was necessary to press an arrow key for the virtual avatar to move. A similar behavior was not observed on P1, P4 or P5, who have low vision; these participants seemed to move more confidently in the VE.

Participants commented on the controls of the virtual avatar and the separation of the walking and viewing directions. P1 declared: “I wasn't very clear on the difference between moving my head and moving my

body". P2 pointed out the importance of feedback on the position of the head: "ok so I need to remember which way I'm looking... That's tricky, that's a problem in some sense because without any feedback of where it is you can forget".

**4.2.3 Need for additional scaffolding.** Participants agreed that spending more time interacting with Echo-House or having a training phase would have improved their understanding of the mouth-click and the echolocation capabilities of Echo-House. According to P3: "it took a while to get used to [the click]. This probably means that for someone to really use this it's just a little bit of training because you're incredibly attuned to the dynamics of your own head for the echolocation". For P4 "it's more a matter of getting used to what the difference in sound means".

P2, P3 and P4 agreed that it is necessary to incorporate additional orientation cues. P4 commented: "if I started turning my head I would lose track of where I was". Similarly, P3 said: "The main thing that I missed was some feedback on the head position", and P2 said: "there isn't enough information to tell which one is the direction I'm facing, and I would just like to have some more clue".

P2 and P3 proposed different solutions to the problem of needing additional orientation cues. P2 suggested: "just hold down Control and left or right to take you to the nearest compass point. This could give me a certain orientation so if I do go too far to the left it'll bring me back on track". P3 suggestion was: "it could be quite easy to add a key that just re centers the head so that you now have a baseline".

### 5 DISCUSSION

Thaler and Goodale [39] argue that echolocation can help blind individuals represent "spatial relationships between objects, or the spatial structure of a scene". Virtual environments (VEs) and videogames contain complex scenes that are almost impossible for people with visual impairment to freely explore, and audiogames provide limited mechanisms for exploration. Addressing these limitations, echolocation could help people with visual impairment make sense of scenes and objects in VEs or videogames by helping them understand the relationships between the spatial objects in these scenes.

The aim of this study was to analyze if it is possible to build a VE that enables participants to simulate echolocation, and to evaluate the feasibility of using echolocation to explore this environment. To achieve this aim, we designed an echolocation-enabled prototype of a VE called Echo-House and tested it with a

group of five participants, including two blind participants who are expert echolocators (P2, P3) and three participants with low vision (P1, P4, P5).

One notable limitation of our evaluation study is that we were only able to recruit a small number of participants. This is because we aimed to recruit individuals who were located on campus of the university where the research took place, and who were blind or had visual impairments, and we decided not to use sighted blindfolded participants to guarantee the relevance of our results. These criteria made it difficult to find suitable participants. Furthermore, this was a feasibility study and we wanted to find out if using echolocation in a VE was possible at all before engaging a larger number of participants.

Sample size is a topic of heated debate in qualitative research, with small samples having limited acceptability in the research community [13, 16]. The key to determining the ideal sample size in qualitative studies is data saturation, which is the point at which no new information or themes appear from conducting more interviews [11, 22]. Guest et al. [22] Boddy [11], and Morse [28] argue that, in order to determine the sample size of a qualitative study, the scope of the study, the quality of the data, the time spent with each participant, and the homogeneity of the population being studied should be considered. Even though the sample size of this study is small, we consider that the scope of this study —being a proof-of concept laboratory-based evaluation—, the time spent with the participants —no less than an hour, with P2, P3, and P5 staying for longer—, the rich quality of the data provided by expert echolocators, and the relative homogeneity of studying a population who share a common trait and similar beliefs, justify the small sample size of this study.

While it could be argued that a participant who is hard of hearing should not be taken into account in a study investigating echolocation, we have decided to keep the insights provided by P5, as they illustrated the limitations of the technique, and the fact that this participant managed to complete all the levels highlights the importance of providing additional means of feedback that are not always present in current VEs.

All participants completed the three levels available in Echo-House, with level (b), the level without echolocation, being the level completed the fastest by most participants, as shown in Table 3. While this result may at first seem counter intuitive, qualitative data reveals this result can be explained by participants taking more time to familiarize themselves with the echolocation features of the program and subsequently



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echolocation could enable people with visual impairment to access virtual environments.

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## 6.5. Discussion

The paper presented in this chapter explores the possibility of using echolocation in a virtual world to complete a navigation task, thus complementing findings presented by the GIC framework in chapter five about the importance of conveying spatial information to improve accessibility in digital games for people with visual impairment. To align this implementation of echolocation in virtual worlds with a critical realist research agenda, off-the-shelf components have been used, and to support an equitably accessible experience, a fully tridimensional environment has been created, instead of relying on a grid-like navigation system.

The quantitative data presented in this chapter indicates that all participants were able to complete the required navigation task. However, participants who can echolocate in the physical world—there were two expert echolocators taking part in this evaluation—took longer to complete the navigation tasks compared to participants who do not echolocate. Moreover, expert echolocators used the echolocating stimulus far more frequently than non-expert echolocators. Although this result may seem contradictory, it occurred because the expert echolocators tried to compare and contrast the experience in the virtual world with their lived experience, hence needing more trials to make sense of the stimulus being received. Furthermore, during the interview stage, the expert echolocators explained that the stimulus and feedback were quite distinct from what they experience in the physical world. However, they recognised that it was possible to learn to use this new stimulus. This finding is not incompatible with the goals of this research, as the aim was not to replicate echolocation as accurately as possible, but rather to create a metaphor to facilitate exploration of virtual worlds.

The interviews also revealed that echolocation may improve participants' sense of presence in virtual environments, as it helps convey a sense of space. However, participants highlighted the need to familiarise themselves with the echolocation stimulus present in the virtual environment, recommending the implementation of a training level or of additional orientation cues. Finally, participants reflected on the controls provided to direct the virtual avatar in the environment—which were mediated via a standard keyboard—and identified difficulty in understanding the difference between controlling the avatar's viewing and walking directions. All these comments will be revisited in subsequent iterations of echolocation-enabled virtual environments.

One weakness of the study presented in this chapter is the attempt to compare three different experimental conditions: echolocation only, voice cues indicating collisions, and echolocation plus voice queues. As I indicated in chapter three, participant recruitment was more difficult than initially expected, and that limited my ability to obtain a larger sample size and conduct statistically significant comparisons. However, the in-depth interviews offer an alternative to the use of inferential statistics, and the combination of the recorded completion times plus participants' opinions registered in the interviews demonstrate that they did find echolocation to be of use to complete the required task.

All in all, this paper demonstrates that it is possible to implement echolocation in such a way that it supports the completion of navigational tasks, even if the implementation does not mimic the real-world experience of echolocation. Additionally, the paper highlights the need to provide scaffolding—aids to support the learning of a new skill (Belland, 2014)—and the need to provide clear controls for virtual avatars. Despite its limitations, this study has successfully demonstrated that it is feasible to implement echolocation in fully tridimensional virtual worlds and use it to support

navigation tasks. The next chapter builds on the findings from this study and provides an in-depth exploration of how people with visual impairment can use echolocation in virtual worlds to acquire spatial knowledge.



# **Chapter 7: Echolocation and Spatial Information in Virtual Worlds**

## **7.1. Introduction**

Chapter two discussed how people with visual impairment acquire spatial information in the physical world and presented a summary of echolocation, including its uses in the physical world and current implementations in virtual worlds. Conversations with expert gamers with visual impairment conducted in study 1 and presented across chapters four and five highlighted their desire to engage with games that are challenging but accessible at the same time, and uncovered the importance of conveying spatial information to improve in-game accessibility. Particularly, participants described how echolocation—which is commonly used in the physical world to acquire spatial information—is sometimes implemented in games, but to a limited extent and using sometimes contradictory metaphors. Study 2A, presented in chapter six, built on this idea and presented a study that assessed the feasibility of using echolocation to complete navigation tasks. This study revealed that it is possible to implement echolocation in fully tridimensional environments using off-the-shelf components and highlighted the importance of having a good mapping with game controls, and the need for orientation cues and proper scaffolding.

This chapter presents the results from Study 2B, which builds on the feasibility study presented in chapter six and provides an in-depth analysis of the spatial information that can be learnt through echolocation in virtual spaces. This chapter focuses on describing how echolocation in virtual worlds can support the acquisition both of landmark and survey knowledge (Kitchin & Jacobson, 1997; Loomis et al., 1993; Siegel & White, 1975). Landmark knowledge refers to the use of specific objects as points of reference that may be placed along a route for orientation purposes (Caduff & Timpf, 2005; Werner et al., 1997). On the other hand, survey knowledge refers to the formation of a mental image or map of space. This image is comprised of landmarks and routes (Cuturi et al., 2016; Thinus-Blanc & Gaunet, 1997).

In Study 2B, landmark knowledge is assessed through participants' ability to identify virtual materials, relative size of rooms, presence of left and right turns, presence of openings, and presence of obstacles. Survey knowledge is assessed through a reconstruction task, where participants are required to recreate the layout of a virtual environment that they explored by using modelling clay. By describing what landmark features of virtual space can be identified through echolocation, this chapter addresses **RQ3**: what features of virtual space can be revealed through echolocation? And by exploring participants' ability to acquire survey knowledge of a virtual world through echolocation, this chapter addressed **RQ4**: How do the features revealed through echolocation support acquisition of spatial knowledge in virtual space?

This chapter presents a paper called "Echolocation as a Means for People with Visual Impairment to Acquire Spatial Knowledge of Virtual Space". The paper has been accepted for publication in the journal *Transactions on Accessible Computing (TACCESS)* and will be published shortly after the final submission of this thesis. This



journal “publishes refereed articles addressing issues of computing as it impacts the lives of people with disabilities<sup>8</sup>”, thus making it a suitable venue for the paper. Similar to previous publications included in this thesis, the paper is included as it will appear in the journal, without any modifications. Furthermore, the references cited in the paper appear as part of the paper instead of in the References list at the end of the thesis.

### **7.2. How this paper contributes to the thesis**

This paper demonstrates that it is possible to implement echolocation in virtual environments in such a way that it supports people with visual impairment in the acquisition of spatial information, both in the form of landmark and survey knowledge. By building on the findings from Study 2A presented in chapter six regarding the need for scaffolding and for orientation feedback, this paper integrates the voices of people with visual impairment into the design process of technologies for them, thus aligning with the critical realist approach followed in this thesis and advancing a rhetoric of designing for empowerment by recognising the unique skills people with visual impairment have developed through their lived experience (Moser, 2000; Rogers & Marsden, 2013).

### **7.3. Data collection and analysis methods**

Similar to the methodology presented in chapters four and six, the paper presented in this chapter follows an explanatory sequential design, as described by Creswell and Plano

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<sup>8</sup> <https://dl.acm.org/journal/taccess>

Clark (2011, pp. 53-106). This design starts with a quantitative phase seeking preliminary answers to the research enquiry, followed by a qualitative phase that provides richer insights into the quantitative results. For the paper presented in this chapter, quantitative data were gathered automatically through a laboratory-based evaluation and qualitative data were gathered through a reconstruction task and follow-up interviews.

The laboratory-based evaluation was divided into two parts. The first part looked at acquisition of landmark knowledge and the second part looked at acquisition of survey knowledge. During the first part of the evaluation, the following quantitative data were collected automatically: whether participants succeeded in each trial—there were several trials where participants had to identify diverse spatial features—the time participants took to complete each trial; the number of times participants used different echolocating stimuli provided; and the number of times participants used the special functions *recentre* and *teleport*. These quantitative data were analysed using a mixed-effects logistic regression, as described by Li et al. (2011), to determine what features—material, size, turns, openings or obstacles—participants were able to detect, thus providing a statistically significant answer to **RQ3**: what features of virtual space can be revealed through echolocation?

During the second part of the experiment, participants had to explore a virtual layout and then rebuild it using modelling clay, thus completing a reconstruction task, as described by Kitchin and Jacobson (1997). Pictures of the models created by participants were taken, and the reconstruction task was followed by semi-structured interviews that aimed to provide rich insights on the overall experience of participants. The reconstruction task and the interviews provided an answer for **RQ4**: how do the features

revealed through echolocation support the acquisition of spatial knowledge in virtual space?

The photos taken of participants' models were used for observational comparison against the actual layout they explored, and the data collected through interviews were analysed using thematic coding, as described by Gibbs (2007). Participants' comments during the interviews centred around how echolocation supported the acquisition of both landmark and survey knowledge, the perceived possibility to perform better over extended periods of interaction with the system, and the perceived real-world applications of echolocation-enabled virtual environments in the lives of people with visual impairment.

### **7.4. The paper**

A PDF file of the paper can be found at <http://go.unimelb.edu.au/n73j>

## Echolocation as a Means for People with Visual Impairment to Acquire Spatial Knowledge of Virtual Space

RONNY ANDRADE\*, JENNY WAYCOTT, STEVEN BAKER, and FRANK VETERE, The University of Melbourne, Australia

In virtual environments, spatial information is communicated visually. This prevents people with visual impairment (PVI) from accessing such spaces. In this article we investigate whether echolocation could be used as a tool to convey spatial information by answering the following research questions: What features of virtual space can be perceived by PVI through the use of echolocation? How does active echolocation support PVI in acquiring spatial knowledge of a virtual space? And what are PVI's opinions regarding the use of echolocation to acquire spatial knowledge of virtual space? To answer these questions we conducted a two-part within-subjects experiment with twelve people who were blind or had a visual impairment and found that: size and materials of rooms, and 90-degree turns were detectable through echolocation; participants preferred using echoes derived from footsteps rather than from artificial sound pulses, and echolocation supported the acquisition of mental maps of a virtual space. Ultimately, we propose that appropriately designed echolocation in virtual environments improves understanding of spatial information and access of PVI to digital games.

CCS Concepts: • **Social and professional topics** → **People with disabilities**; • **Human-centered computing** → *Auditory feedback*; *Accessibility technologies*.

Additional Key Words and Phrases: echolocation, visual impairment, virtual world, exploration

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## 1 INTRODUCTION

People with visual impairment (PVI) have difficulty accessing digital games due to the inherently visual nature of such games [15, 98]. Although some solutions for PVI to engage with digital games have emerged, particularly in the form of audiogames and text-based adventures, providing PVI access to mainstream gaming experiences remains a challenge [4, 38, 85]. One particular challenge PVI face when engaging with digital games is difficulty in acquiring information about the spatial characteristics of the virtual world. People encode spatial information as landmark, route and survey knowledge [13, 39, 67, 69, 82]. While there is an extensive body of literature exploring acquisition and evaluation of spatial information by PVI in the *physical* world, little is known about how PVI acquire spatial information of virtual spaces, and how this acquisition supports PVI's engagement with digital games.

\*Corresponding author

Authors' address: Ronny Andrade, [andrader@unimelb.edu.au](mailto:andrader@unimelb.edu.au); Jenny Waycott, [jwaycott@unimelb.edu.au](mailto:jwaycott@unimelb.edu.au); Steven Baker, [steven.baker@unimelb.edu.au](mailto:steven.baker@unimelb.edu.au); Frank Vetere, [f.vetere@unimelb.edu.au](mailto:f.vetere@unimelb.edu.au), The University of Melbourne, Parkville, VIC, Australia, 3010.

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In this paper, we report on a study which investigates the use of active echolocation—the use of sounds and echo reverberations over surfaces [40, 42]—as a way to improve access to spatial information for PVI engaging with virtual worlds. We evaluated how echolocation supported the understanding of the following landmark features of the virtual space: the material and relative size of rooms, 90-degree turns, openings in walls, and obstacles. These elements have been identified as being detectable through echolocation in the physical world [18, 40, 50, 73, 75, 78, 79]. Additionally, we evaluated the use of echolocation to support acquisition of survey knowledge and to enable PVI to form a mental map of virtual space. Specifically, we addressed the following research questions: *RQ1*: What features of virtual space can be perceived by PVI through echolocation? *RQ2*: How does active echolocation support PVI in acquiring spatial knowledge of a virtual space?, and *RQ3*: What are PVI’s opinions regarding the use of echolocation to acquire landmark and survey knowledge of virtual space?

Upon conducting a two-part user study with twelve blind or visually-impaired participants, we found that: (i) virtual materials, relative sizes of rooms and 90-degree turns were easier to perceive with echolocation than openings and obstacles; (ii) echo derived from footsteps had a central role in the acquisition of both landmark and survey knowledge; and (iii) several participants developed an accurate mental map of a virtual space through the use of echolocation and could satisfactorily complete a reconstruction task. By working together with a group of PVI, our study recognises the unique skills they have developed through their lived experience.

## 2 AIMS AND CONTRIBUTIONS

The aim of this work was to evaluate the usefulness of active echolocation as a means for people with visual impairment (PVI) to acquire spatial knowledge of virtual environments. While previous work has established the importance of conveying spatial information to improve accessibility in virtual worlds [5] and presented echolocation as a means to explore these worlds [3, 95], their scope had been limited to feasibility studies that did not look at spatial knowledge acquisition. Unlike previous research conducted with sighted individuals, [23, 25, 56] our work emphasises the importance of the lived experience of PVI as a source of knowledge.

We extend prior work by adapting a systematic approach to evaluate echolocation as a tool for PVI to acquire spatial knowledge of virtual environments. Our evaluation study explicitly identifies the landmark features of a virtual space that PVI can perceive through echolocation, namely: virtual materials, relative size of virtual rooms, 90-degree turns, openings and obstacles. Furthermore, we show that some features are more difficult to convey through echolocation than others. Ultimately, we propose that appropriately designed echolocation in virtual environments improves understanding of spatial information and access of PVI to digital games. [59].

## 3 PREVIOUS WORK

In this section, we describe the concepts of landmark, route and survey knowledge and how these concepts relate to acquisition of spatial information in the physical world. Additionally, we describe echolocation, how it has been used to acquire spatial knowledge, and previous attempts to implement it in virtual worlds.

### 3.1 Acquisition of spatial information

It has been argued that sight is crucial for the development of spatial knowledge [82]; however, other sensory input, such as hearing, can potentially provide the basis for the spatial perception required to develop awareness of space [20]. Spatial knowledge has been classified into three types: landmark, route and survey knowledge [69, 89]. In the following sections, we describe these three types of knowledge and how they relate to each other. In this study we are primarily concerned

with landmark and survey knowledge; we do not focus on route knowledge during this study because we wanted participants to have a flexible experience where they would have agency over the path they would follow to explore the virtual environment.

**3.1.1 Landmark and route knowledge.** Landmarks are fixed objects in specific locations that are typically integrated in routes [14, 92]. Landmark knowledge is more effective for navigation than knowing street names and estimating distances [14, 83]. Caduff and Timpf argued that an appropriate representation for landmarks in virtual worlds helps identify "relevant aspects from the physical environment" [14]. In our work, landmark knowledge refers to specific relevant features from the physical world that have been replicated in the virtual world, instead of fixed objects. These features are: different materials, sizes of rooms, 90-degree turns, openings and obstacles.

Routes are a sequence of steps that guide a person from point A to point B and usually integrate landmarks [39]. PVI tend to stick to known routes in order to avoid disorientation and getting lost [39, 82]. However, the sequential nature of routes makes them inflexible and an error in one step in the route may leave the person stranded [82]. A more holistic approach to navigation is afforded by survey knowledge.

**3.1.2 Survey knowledge and mental maps.** Survey knowledge is different from route knowledge in that it is the conceptualisation of space "as a whole" and relies on the division of space into "smaller, clearly connected, more manageable pieces" [22]. Survey knowledge provides a person with a "mental map" of their surroundings [20]. Mental maps are similar to a bird's eye view of space. Mental maps lead to spatial representations that "are more fine-grained than route descriptions" [53].

In order to acquire survey knowledge in virtual spaces, it is recommended that PVI: divide the space into distinct small parts, find a principle under which to organise the small parts, and receive frequent directional cues [21, 22]. These recommendations have been implemented in experimental virtual worlds and digital games targeted to PVI through the use of grid-like navigation systems [6, 17, 29]. However, this approach limits in-game movement to four pre-established directions, thus reducing agency of PVI.

**3.1.3 Evaluating acquisition of survey knowledge.** Exploration tasks, where participants are asked to explore a space freely, are commonly used to acquire survey knowledge in both physical and virtual worlds [1, 22, 43, 44]. However, survey knowledge is difficult to assess. Kitchin and Jacobson [39] have provided a summary of strategies to assess survey knowledge. One such strategy is the use of reconstruction tests, in which participants are required to replicate the layout of a space they have previously explored. Reconstruction tests may require participants to use a modelling kit with building blocks that represent elements of an environment [39, 43, 44], or may provide participants with flexible materials, such as modelling clay, for them to recreate the environment from scratch [1]. Previous works have used reconstruction tests to assess acquisition of survey knowledge and formation of mental maps in the physical world [39, 90] and in virtual worlds [1, 44]. However, Kitchin and Jacobson acknowledge the issues of validity that surround reconstruction tests and recommend the use of a combination of different assessment tasks to triangulate the accuracy of the knowledge acquired. To address such issues of validity, researchers have used recall and reconstruction questions [33], a combination of open interviews with reconstruction tasks [44], or a combination of interviews, usability questionnaires and recall questions [1].

## 3.2 Echolocation

Echolocation is the ability of certain mammals—including bats, dolphins and humans—to use self-generated sounds and their reverberations over surfaces to obtain spatial information of their

surroundings [40, 42, 81]. Echolocation may be passive or active. Passive echolocation requires a person to listen to the echo produced by environmental sounds [8, 73]. Conversely, active echolocation requires a person to actively produce sounds, with commonly-used sounds including sharp clicking sounds with the tongue, footsteps, hitting the floor with a white cane, and clapping. In the physical world, Rojas et al. have found that tongue-clicks are the best sound for echolocators [63]. Although there are no statistics available on the number of people who can echolocate, anecdotal reports in the literature suggest 20-30 percent of PVI use some form of echolocation [78]. Moreover, those capable of using this technique are shown to have an overall better performance in orientation and mobility tasks [78, 89]. However, research recognises that echolocation is not used in isolation, but rather as an additional tool for PVI to explore their surroundings [78].

There has been an increased interest in echolocation as a technique for PVI to explore the physical world. Research in the field of neuroscience has explored the biological mechanisms behind human echolocation [7, 42, 50, 79]. Moreover, researchers have produced cane-like devices to simulate echolocation and assist PVI with the navigation of the physical world, obtaining favourable results in their evaluations [88, 90].

Echolocation can be used to identify landmark features of a person's physical surroundings. Research has assessed the ability of PVI to identify: distance and shape of objects [64, 73], size of objects [40, 50], whether an object is moving or stationary [73, 79], the material an object is made of [37, 40, 78] and whether a collision with an obstacle is imminent [18, 75, 78]. These features are identifiable due to the difference in pitch and volume of echoes as they reach the left and right ear [18, 73, 78]. While there is a significant body of literature exploring the range of features that can be identified through echolocation, there is scant information on how echolocation may support the acquisition of survey knowledge and the formation of mental maps in PVI.

*3.2.1 Echolocation in virtual worlds.* In recent years, there has been more interest in the use of echolocation to explore virtual worlds. Ramos and Arias [61] proposed the use of a C++ library and specialised hardware to simulate clicks produced by echolocators. A study by Thaler et al. proposed the use of artificial clicking sounds as a first step towards virtual echolocation. Thaler et al. [81] synthesised artificial clicks from recordings of sounds produced by expert echolocators and have developed a dataset and Matlab code to create artificial clicking sounds. Their experiment did not provide further evaluation of their artificial clicking sounds. Preliminary studies from the field of sound engineering have explored whether echolocation can be replicated in digital spaces through virtual avatars. Wu et al. [95] created a mobile game that allowed players to explore a maze-like environment through a grid-like navigation system. This mobile application used pre-recorded echoes and its aim was to teach how to use echolocation in the physical world. Wu et al. [95] found that participants could successfully avoid virtual walls.

Andrade et al. [3] conducted an experiment where a small group of PVI trialed a virtual world where participants used echolocation and spatialised binaural sound to locate targets. In this study, Andrade et al. identified a set of freely available game development tools that could be used to simulate echolocation in virtual worlds—specifically the game development tool *Unity* and the plug-in *SteamAudio*. Andrade et al. [4] also highlighted the importance of providing proper scaffolding when learning how to use echolocation in virtual worlds and discussed the importance of conveying spatial information to improve in-game accessibility [5]. Neidhardt et al. [51, 52] evaluated the ability of blind individuals to locate a wall in virtual reality through the use of echolocation and found that participants were able to identify walls at distances of 20-30cm.

Evaluations of echolocation in virtual worlds with sighted people have been conducted. Flanagan et al. [25] found that sighted subjects are able to identify variations in sizes of virtual rooms,

especially when they actively produced vocal sounds. Similar to Neidhardt et al. [51, 52], Pelegrin-Garcia et al [56], have found that sighted individuals are also able to identify a wall in virtual reality. Dodsworth et al. [23] have found that sighted individuals are able to judge the spatial layout of a virtual environment after several training sessions. The body of research presented in this section shows that it is possible to replicate echolocation in virtual environments. However, our study complements these previous studies by being the first to evaluate a wider range of spatial knowledge acquisition of a virtual space through echolocation exclusively with visually-impaired participants.

#### 4 METHODOLOGY

In this paper, we present the results of a two-part within-subjects laboratory-based evaluation exploring how echolocation may support PVI in acquiring spatial knowledge of a virtual space. To this end, we built a custom echolocation-enabled virtual world. The first part of the experiment focused on landmark knowledge, required participants to explore a training space and five levels—each level evaluating a specific landmark feature—and complete several trials per level. The second part of the experiment focused on survey knowledge and required participants to freely explore a virtual space for half an hour and then complete a reconstruction test where they had to replicate the space with modelling clay [1, 39]. In this section, we provide a description of the virtual world we created, the sounds that were available to participants, the design of each part of the experiment, participants' demographic information and data collection and analysis strategies.

##### 4.1 Design of the virtual world

The virtual world used in both parts of the experiment was created using *Unity 3D* version 2018.3 and the *SteamAudio* plug-in version 2 beta 10. The use of the *SteamAudio* plug-in allowed us to simulate real-time physics-based sound propagation. Moreover, the plug-in allowed for the simulation of sound absorption and reflection of different materials over virtual objects, sound occlusion by objects and the use of a generic head-related transfer function (HRTF) to simulate how sound reaches the left and right ear at different times. Sound reflections were of first order. First order reflections occur as sound leaves its source and hits the boundaries of the room (walls and ceiling). We modelled first order reflections because these provide a good trade-off between accuracy and required computing power [28].<sup>1</sup>

We chose to use a generic HRTF because the *SteamAudio* plug-in did not support individualised HRTFs by the time we conducted our experiment and because obtaining individualised HRTFs requires the use of an HRTF measuring apparatus in an anechoic chamber [49], to which we did not have access. Moreover, the use of best-match HRTFs have been found to not have a significant difference in participants' performance in certain audio-based tasks [58], and generic HRTFs have been found to be "good enough" for virtual worlds, when multi-sensory stimuli are provided [11].

For the first part of the experiment, we designed a training level and five experimental levels. For details on the training level, see the section *Accessibility testing*. Each experimental level assessed a different feature that PVI who use echolocation in the physical world can identify, as described in the literature [40, 50, 64, 73, 80]; specifically, the features assessed were: materials and size of rooms, 90-degree turns, openings and presence of obstacles. For experiment two, we designed a single level that combined the following features assessed in experiment one: rooms of different size, 90-degree turns and the presence of openings, while using the same material for the entire level and not including any obstacles. In all experimental conditions, the material simulated with

<sup>1</sup>More information on how *SteamAudio* handles sound effects can be found in the project site [https://valvesoftware.github.io/steam-audio/doc/phonon\\_unity.html](https://valvesoftware.github.io/steam-audio/doc/phonon_unity.html).



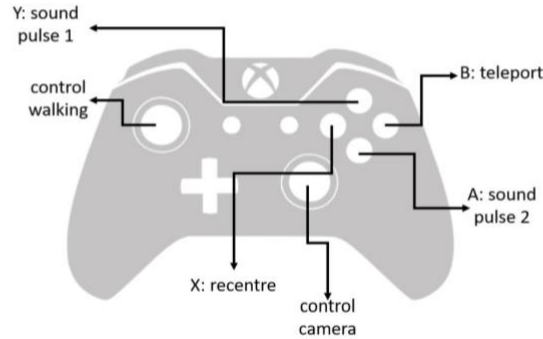


Fig. 1. Layout of the controls provided in the Xbox controller

the *SteamAudio* plug-in was concrete (unless otherwise specified), the virtual rooms had a height of three units, and the virtual walls had a thickness of 0.6 units. <sup>2</sup>.

For both experiments participants used Audio Technica ATH-M40x headphones. We chose these headphones because they provided a flat audio response without the bass enhancement common to other headphones. In both parts of the experiment participants controlled a digital avatar obtained from the *Unity* Standard Assets. The avatar provided participants with a first-person perspective while completing the experimental tasks. Furthermore, a *SteamAudio Source* component was added at the top of the avatar model to simulate the emission of the synthesised artificial mouth clicks from a person's head. The avatar was also equipped with a *SteamAudio Listener* positioned at the top of the avatar model. *SteamAudio* generic HRTF and the positioning of the *SteamAudio Listener* modelled how sounds in the virtual world reached participants' ears.

Participants used an Xbox controller to control the virtual avatar. Mainstream gaming console controllers have been adapted before for use by PVI [15, 76, 93]. The left joystick controlled the walking direction of the avatar while the right joystick controlled the viewing direction of the first-person perspective. Both joysticks provided constant movement, as is the case in mainstream videogames. Similarly, the avatar continued to "walk" even when colliding with a wall and no auditory feedback was given to indicate collision; this was to prevent collision feedback from becoming a confounding factor. The *Y* and *A* buttons produced two distinct artificial sound pulses synthesised from the data obtained from Thaler et al. [81] from two expert echolocators; the *X* button allowed participants to return to the original position where they spawned on each level (recentre), and the *B* button allowed participants to change between different rooms in levels one and two of the first part of the experiment (teleport). Each time participants teleported, the virtual avatar was positioned in the bottom-centre of the new room. Figure 1 shows the the controls available to participants.

## 4.2 Feedback mechanisms

We provided participants with three means of active echolocation: two artificial sound pulses, and the use of footsteps. The sound pulses were produced based on the research of Thaler et al [81], who collected samples of mouth-clicks produced by three expert echolocators and provided a dataset and computational model in Matlab to replicate these mouth-clicks in virtual worlds. From Thaler et al.'s [81] data, we chose to use the datasets from the two expert echolocators that

<sup>2</sup>Entire Unity project, assets and dependencies for the virtual world available at: <http://bit.ly/virtual-echolocation>

contained the lowest variance across samples to provide pulses that were consistent. We used the Matlab code provided by Thaler et al. [81] to produce the clicking sounds. This resulted in two artificial clicks of 7ms in duration and with peak frequencies in the 2-4Khz range. As these sounds were synthesised from different data sets, their spectral content was different in each, effectively resulting in two distinct sounds. Furthermore, we included two artificial clicking sounds to better simulate echolocation as it occurs in the physical world, where no two mouth-clicks are exactly the same. The footsteps were provided by default with the avatar included in the *Unity* Standard Assets. The footstep sounds were produced as the avatar, which participants controlled, walked around the virtual world.

In the physical world echolocation is not used in isolation, but rather is used as a complementary means to obtain information [78]. Moreover, previous studies on echolocation in virtual worlds have identified the need to provide additional feedback mechanisms [3, 95]. To address these concerns, we provided the following additional spoken cues:

- *Compass points*: participants heard the compass point they were facing as they moved the avatar's viewing angle around with the Xbox controller using the left joystick.
- *Level description*: at the beginning of each trial for part one of the experiment participants heard the feature being tested and the goal they had to accomplish. In part two, participants were told to freely explore the virtual world for half an hour or until they could create a mental map of it and then replicate it with modelling clay.
- *Other feedback*: participants heard the message "recentred" when they pressed the *X* button. Similarly, when participants pressed the *B* button, they would hear the message "Teletransport".

These cues were available in both parts of the experiment and through our accessibility test we ensured that the instructions did not reveal the spatial information that was being assessed.

### 4.3 Experimental design: part one

In this part, participants explored a training level, as described in the *Accessibility testing* section. This training level consisted of a 12x12 square room made of virtual concrete. While in the training level, participants became familiar with the Xbox controller and the commands afforded by it. The commands are presented in Figure 1, thus learning how they could interact with the virtual world through the controller. The training level was included following advice from an accessibility expert who assessed the study setup (described in the *Accessibility testing* section) and suggested that participants would need to feel comfortable using the hand controller before they could do the experiment. The section *Accessibility training* describes how participants were introduced to each command of the Xbox controller. The training level did not include training on interpreting the sounds and feedback. However, if participants asked questions such as "is there a wall to my left?" or "Am I close to a corner?" they were given a yes or no answer. The training level was designed for participants to familiarise themselves with the controller, so no training was provided on how to differentiate different materials, sizes of rooms, etc.

After spending as much time as desired in the training level, participants proceeded to explore five levels in a virtual world and performed several 3-minute trials per level. Each level was designed so that participants had to identify: the material a room was made of, the relative size of rooms, the presence of 90-degree turns, openings and obstacles. Each trial introduced an element of variability to prevent learning effects from affecting our results. Table 1 presents a description of each level, including the number of trials per level, the goal of each level, the task participants needed to perform in each level, the success criteria, and the variability factor introduced to prevent learning effects from confounding our results.

| Level | Trials | Goal               | Task                                                                                | Success criterion                                                        | Variability                                                                                    |
|-------|--------|--------------------|-------------------------------------------------------------------------------------|--------------------------------------------------------------------------|------------------------------------------------------------------------------------------------|
| 1     | 7      | Identify materials | Participants teleport at will across three 8x8 rooms made of: carpet, wood or metal | Participants identify the material any of the rooms is made of           | Participants start on any of the three rooms at random                                         |
| 2     | 7      | Identify size      | Participants teleport at will across three rooms of size: 8x8, 12x12 and 16x16      | Participants identify the relative size of any of the rooms              | Participants start on any of the three rooms at random                                         |
| 3     | 6      | Identify turns     | Participants explore an L-shaped room                                               | Participants identify whether the turn is to the left or to the right    | The turn may be located on the top-left, top-right, bottom-left or bottom-right of the room    |
| 4     | 6      | Identify openings  | Participants explore a 12x2 corridor with an opening                                | Participants identify whether the opening is to the left or to the right | The opening may be located in the middle-left, middle-right, top-left or top-right of the room |
| 5     | 8      | Identify obstacles | Participants explore a 16x16 room with a 2x2 column that acts as an obstacle        | Participants identify when the obstacle is in front of them              | The obstacle appears in any position at random within the room                                 |

Table 1. Description of each level for experiment part one

There were 7 trials for exploration of materials and size (levels 1 and 2); 6 trials for exploration of turns and openings (levels 3 and 4) and 8 trials for exploration of obstacles (level 5). Participants first completed 7 trials for level 1 before moving to level 2, then they completed 7 trials for level 2 before moving to level 3, and so on. In levels 1 and 2, participants teleported cyclically among rooms that were designed as if they were made of carpet, then wood, then metal (level 1) or rooms of small, medium and large size (level 2). The initial room would be assigned randomly but the teleporting sequence was fixed, as described in Table 1. As the sequence of rooms did not change, participants were only required to successfully identify one room for the trial to count as successful. We purposefully decided not to randomise the order of the levels to address findings from previous research regarding the need to provide scaffolding to learn to use echolocation in virtual worlds [3]. Although participants went through levels 1 to 5 in order, each individual trial was different, as an element of variability—described in Table 1—was randomly introduced. The number of trials for each level was calculated based on the need to achieve sufficient estimation of binomial distribution for small samples [66, p. 106-125]. The number of trials per level depended on: the desired level of confidence of the results (95% confidence in our case), a critical difference parameter that we set to 0.1, as we originally expected to conduct our evaluation with ten participants, and the success rate of a previous evaluation, which was 0.33 for levels 1 and 2, 0.25 for levels 3 and 4, and 0.5 for

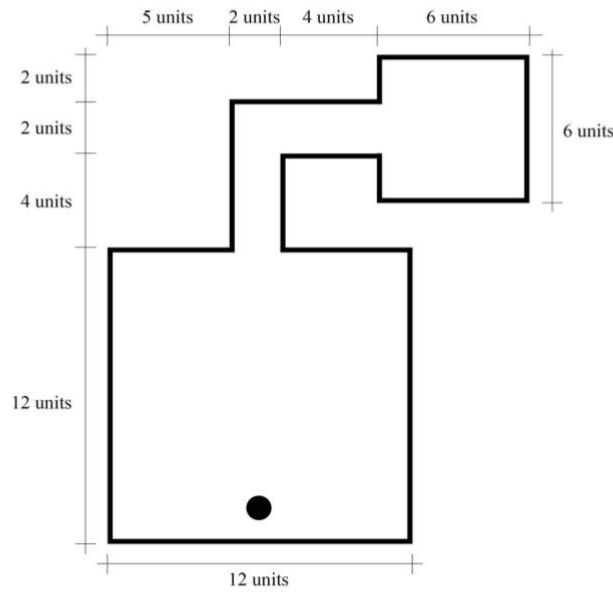


Fig. 2. Layout of the level used in part two of the experiment

level 5. This success rate corresponded to the probability of participants succeeding in each level by chance alone, considering the different variability conditions described in Table 1.

Each participant conducted a total of 34 trials and had three minutes to complete each trial. The number of individual trials per level is presented in Table 1. This number of trials amounted to 102 minutes of experimentation per participant. After conducting the experiment, participants were invited to take part in a semi-structured interview to explore their opinions about the usefulness of echolocation to identify landmark features of virtual space. The interview questions aimed to find out what experience participants had previously had with digital games and virtual worlds, how they acquire spatial knowledge in the physical world, what level they found easiest/hardest and why, and what were their general opinions about each level. Interviews had an average length of twelve minutes per participant, for a total estimated time of two hours for this part of the experiment per participant. To reduce participants' fatigue, they were offered a five-minute break upon completing level three—equivalent to having completed 20 trials—and a ten minute break after the post-interview.

#### 4.4 Experimental design: part two

In this part of the experiment, we investigated how echolocation aided participants to acquire survey knowledge and form a mental map of a virtual space. For this part, participants were required to explore the virtual space shown in Figure 2 for thirty minutes, or until they were satisfied they had a clear image in their heads of the shape of the virtual space, with all participants starting in the place marked with a black dot in Figure 2. Part two of the experiment was conducted immediately after the ten-minute break at the end of part one.

Upon completing the exploration of the virtual space, participants were required to complete a reconstruction test, where they were given the instruction to replicate the layout of the virtual space they had just explored using modelling clay. Upon completion of the clay models, participants took part in a semi-structured interview, where they were asked about their previous experience

with reconstruction tests, how they had perceived space in the virtual world, the role of the different feedback mechanisms provided, and if they had any final thoughts about the use of echolocation as a means to acquire spatial knowledge. The total duration of this part of the experiment was approximately 45 minutes per participant.

#### 4.5 Accessibility testing

Upon completing the design of our virtual world, we conducted an accessibility test to assess if the instructions provided at the beginning of each level were clear, and if the mapping of the controls was logical. Considering that the goal of the test was not to evaluate the usability of echolocation in a digital world, we ran the test with the University Web Accessibility Lead, someone who does not have a lived experience with a visual impairment but has experience working with assistive technologies.

Through the test we identified that the verbal instructions provided at the beginning of each level were clear and the controls were appropriate. However, the test also helped us identify the need for a training level to teach participants how to use the Xbox controller. As the Web Accessibility Lead put it: *"If you give your participants a control they don't know how to use, that's going to affect your results because they'll spend a considerable amount of time learning how to use the control."*

The training level introduced participants to each command afforded by the Xbox controller separately, starting with the left joystick of the Xbox controller (used for walking), then the right joystick (used for controlling the direction of the camera), the *Y* and *A* buttons (used to produce the artificial sound pulses) and finally the buttons *X* and *B* (for re centring the virtual character, or teleporting between rooms, correspondingly). Participants could remain in the training level and try each control for as long as they pleased. In practice, participants spent almost 13 minutes—or around 780 seconds—on average in the training level ( $M = 775.92$  seconds,  $SD = 203.31$  seconds). By doing this, participants became familiar with how the virtual world operated.

#### 4.6 Participants

Participants were recruited via snowball sampling amongst the contacts of the first researcher, who has several years of experience working with people with visual impairment. We recruited twelve participants for our experiment. Each one participated in both parts of the experiment. Two participants identified as female and ten as male. As participants were self-selected, we could not control for gender bias. As participants were selected amongst the contacts of the first author, we have not included other details of their identity such as specific age or cause of blindness, as this could lead to their de-anonymisation. Nine participants were completely blind, two were blind with light perception, and one had low visual acuity, perceiving mostly colours. P3, P7, P8 and P12 used echolocation, with P7 and P12 actively producing mouth-clicks to echolocate, and P3 and P8 listening to echoes produced by their cane or their speech. All participants used a white cane and have used computers for five years or more. All participants were rewarded with a 30 USD gift card for three hours of their time for both parts of the experiment. Table 2 shows demographic information of our participants.

Previous research on echolocation involving sighted participants and PVI has found that there is considerable variability in the echolocation abilities of these two groups [65, 77], with PVI being on average better echolocators than sighted individuals [40, 65]. Moreover, PVI develop specific navigation strategies that are not familiar to sighted people [72] and employing sighted blindfolded individuals only replicates *the initial shock* of losing a sense, but does not capture the rich set of skills of people with lived experience of visual impairment [70]. For all these reasons we did not include blindfolded individuals in our experiment.



| N   | Age range | Gender | Impairment (and onset)              |
|-----|-----------|--------|-------------------------------------|
| P1  | 46 to 55  | Male   | Blind, from birth                   |
| P2  | 36 to 45  | Female | Blind, from 18yo                    |
| P3  | 46 to 55  | Male   | Blind, as adult                     |
| P4  | 46 to 55  | Male   | Blind, as adult                     |
| P5  | 46 to 55  | Male   | Blind, as adult                     |
| P6  | 26 to 35  | Male   | Low visual acuity, from birth       |
| P7  | 26 to 35  | Male   | Blind, from birth                   |
| P8  | 18 to 25  | Male   | Blind, light perception, as a teen  |
| P9  | 26 to 35  | Female | Blind, from 21yo                    |
| P10 | 46 to 55  | Male   | Blind, from 18yo                    |
| P11 | 18 to 25  | Male   | Blind, light perception, from birth |
| P12 | 56 to 65  | Male   | Blind from birth                    |

Table 2. Demographic information of participants.

#### 4.7 Data collection and analysis

We captured the following quantitative data during the first part of the experiment: success, defined as a binomial variable evaluated against the success criteria defined in Table 1 (*success*), the time participants took to complete each trial (*time\_trial*), number of times participants used artificial sound pulses one and two (*tone\_1*, *tone\_2*), number of times participants used the recentre function (*recentre*), and for levels one and two we captured the number of times participants used the teleport function (*teleport*). Additionally, we captured the duration of participants' stay in the training level (*training\_time*). For part two of the experiment we captured observations of participants' clay models via pictures. For both experimental phases we captured video recordings of participants' interactions and audio recordings of post-interviews.

We used mixed-effects logistic models to explore: 1) what landmark features were easier to identify by participants (RQ1), and 2) any association between success rates and the use of the artificial sound pulses (RQ2). We chose logistic models, which are a sub-category of generalised linear models, because the outcome variable, *success*, was binary. A mixed-effects model was required because each participant made multiple trials [45, 48]. We used the statistical software R in our data analysis [60], and to fit our mixed-effects models we used the *lme4* package [9]. To test for association between explanatory variables and the outcome, we conducted a type-III analysis of variance (ANOVA) with the *car* package [26]. To further explore RQ2, we also computed means and standard deviations of the use of *tone\_1* and *tone\_2* to observe any trend in the use of the artificial clicking sounds and the level being explored.

In addition to our quantitative data, we collected qualitative data about the participants' experiences via post-interviews. Following an explanatory sequential approach [19, p. 53-106], qualitative data were used to provide a greater degree of depth on the quantitative findings when addressing RQ1 and RQ2. Furthermore, RQ3 is answered with qualitative data. The first author analysed the qualitative data using thematic coding, as described by Gibbs [30]. The first step in this analysis was to transcribe all interviews, then to create preliminary codes for the data, grouping similar ideas under the same code. The resulting codes were established based on how they related to each research question. We support the argument that thematic coding and analysis are interpretative exercises whose goal is not to obtain "one single truth" [12, 55], so we decided to forego inter-coder analysis. Furthermore, the lived experience of the first author as someone with visual impairment

| Level       | Probability of success | Confidence Intervals |
|-------------|------------------------|----------------------|
| 1.Material  | 0.75                   | 0.63, 0.85           |
| 2.Size      | 0.64                   | 0.50, 0.76           |
| 3.Turns     | 0.71                   | 0.57, 0.82           |
| 4.Openings  | 0.40                   | 0.27, 0.54           |
| 5.Obstacles | 0.43                   | 0.31, 0.56           |

Table 3. Predicted probabilities of success for each level

| Contrast | Odds ratio | Confidence intervals | p-value |
|----------|------------|----------------------|---------|
| 1 / 2    | 1.7        | 0.86, 3.36           | 0.124   |
| 1 / 3    | 1.3        | 0.61, 2.58           | 0.533   |
| 1 / 4    | 4.6        | 2.29, 9.38           | <.001   |
| 1 / 5    | 4.0        | 2.06, 7.67           | <.001   |
| 2 / 3    | 0.7        | 0.37, 1.47           | 0.388   |
| 2 / 4    | 2.7        | 1.39, 5.33           | 0.004   |
| 2 / 5    | 2.3        | 1.25, 4.35           | 0.008   |
| 3 / 4    | 3.7        | 1.81, 7.54           | <.001   |
| 3 / 5    | 3.2        | 1.62, 6.17           | <.001   |
| 4 / 5    | 0.9        | 0.45, 1.63           | 0.640   |

Table 4. Pairwise comparison between levels

may afford him insights into the coding process that would not have been available to the other authors.

## 5 RESULTS

In this section we discuss quantitative and qualitative results of our study, as they pertain to each of the three research questions. Part one of the experiment provided results for *RQ1* and *RQ2* concerning landmark knowledge. Part two of the experiment provided results for *RQ2* concerning survey knowledge (and mental maps) and *RQ3*.

### 5.1 RQ1: What features are perceived through echolocation?

**5.1.1 Quantitative results.** To analyse the quantitative data from **part one** of our study, we used a mixed-effects logistic regression model with *level* as a categorical fixed effect, *participant* as a random effect and *success* as the outcome. Our model showed that *success* varied by *level* ( $p < 0.001$ ).

Our next step was to compute the predicted probability of success for each *level*, along with 95% confidence intervals. The results are shown in table 3. The table presents the level, the probability that a participant succeeded by level, and lower and upper confidence intervals. The table shows that the probability for succeeding in each level was: 75%, 64%, 71%, 40% and 43% for levels 1, 2, 3, 4 and 5, respectively. This indicates that participants were more successful identifying size and material of rooms, and 90-degree turns, than openings and obstacles. Qualitative data shown later suggests this is an effect of our scaffolded approach to designing the levels.

Additionally, we conducted pairwise comparisons between the different levels. The results of this comparison are presented in Table 4. The table presents the two levels being contrasted, the

odds ratio and 95% confidence interval, and p-value of each comparison. Contrasts with p-values lower than 0.05 were considered statistically significant. The table shows a statistically significant difference between the following pairs of levels: 1/4, 1/5, 2/4, 2/5, 3/4, 3/5. This means that levels one (materials), two (size) and three (turns) are significantly different in difficulty from levels four (openings) and five (obstacles). Qualitative findings clarify how these levels are perceived to have increasing difficulty by participants.

**5.1.2 Qualitative results.** In relation to *RQ1*, qualitative analysis of the interviews conducted during **part one** of our study revealed participants' thoughts on how the first part of the experiment was scaffolded—with the "easiest" levels first. Almost unanimously, participants reported that the easiest levels were levels one (materials), two (size) and three (turns), showing agreement with the results in Table 3. With respect to the materials and how echolocation helped identify them, participants related the sound to their lived experience. For instance, P3 commented: *"I used to live in a house with a wooden floor, and that sound with the sound of carpet is, like, engraved in my ears, because I have experienced them, so I could identify the sound easily."* P11 complemented this by saying *"when you walk on a carpet, there is almost no sound, there is no echo. But when you walk by a metal, there's a lot of echo."* Participants' comments highlighted the relation between in-game sounds and real-world sounds.

In regards to the second level with rooms of different sizes, P8 said: *"The sizes one was easier to me because in a bigger space the echo lasts longer, and in a smaller place the echo lasts less."* P2, P9, and P10 made very similar remarks. In regards to the detection of 90-degree turns, P9 said: *"when I got to that point where the room would open, where the room would get wider, I would say, 'here it is.'"* P12 described a similar situation: *"I was essentially walking the length of the corridor forward and then backward and that was, indeed, to get the sense [of] 'ok so here's the opening!'"* Participants' comments demonstrated how they perceived changes in virtual space through echolocation.

Participants agreed that levels four and five—detecting openings and obstacles—were the most difficult. These opinions matched the results from Table 4, which showed that levels four and five were significantly distinct from levels one, two and three. Of these levels, participants commented they found it *"very difficult to locate the objective"* (P1). According to P2, the obstacle of level five *"is not discernible"*, with P5, P6 and P12 expressing similar comments. Moreover, P2, P5, P10, P11 and P12 agreed that there was a progression in the complexity of the levels. According to P2: *"[Up] until the third level, it was easy, then after easy it became more difficult"*. More specifically, P7 described a progression between levels two and three: *"the second level is [like] an entrance to the third level... If you cannot determine the size, you will not find the opening of the L"*. While participants referred to a sense of progression, their performance in later levels did not improve, as demonstrated by the results in Table 3.

## 5.2 RQ2: How does active echolocation support PVI in acquiring spatial knowledge of a virtual space?

**5.2.1 Quantitative results.** While spatial knowledge refers to both landmark and survey knowledge, we began by analysing how echolocation supports the acquisition of landmark knowledge through analysis of quantitative data from **part one** of our study. To this end, we produced a mixed-effects logistic regression model with the quantitative data gathered during part one of our experiment. We used *level*, *tone\_1*, *tone\_2*, *time\_trial*, *recentre* as fixed effects, *participant* as random effect, and *success* as the variable to be predicted. We did not observe a statistically significant effect of *tone\_1* ( $p = 0.477$ ), *tone\_2* ( $p = 0.622$ ), *time\_trial* ( $p = 0.099$ ) or *recentre* ( $p = 0.125$ ) on *success*. Therefore, we cannot conclude that the frequency of use of the artificial sound pulses was associated with participants' success rates.



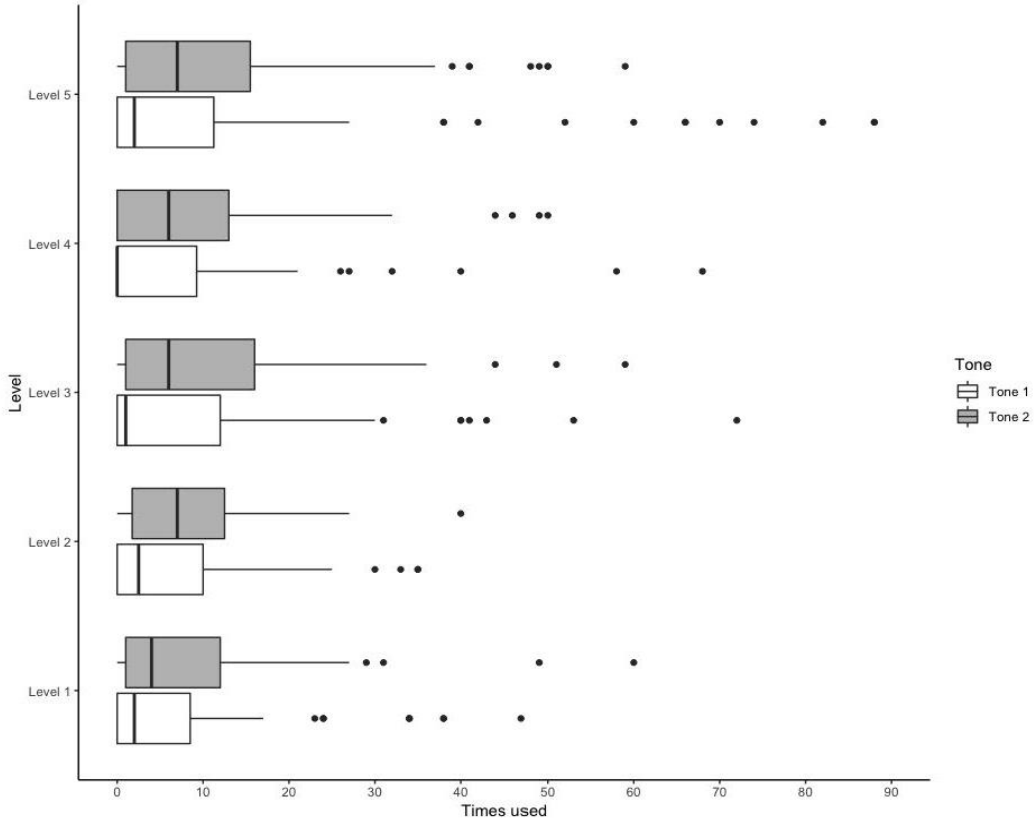


Fig. 3. Boxplots of the use of *tone\_1* and *tone\_2* by level. These indicate a very slight preference for *tone\_2* and show a number of outliers

Further analysis of participants' use of *tone\_1* and *tone\_2* is presented in Figure 3. The Figure provides an overview of quarterlies 1, 2 and 3 for the distribution of the use of *tone\_1* and *tone\_2* by *level*. The means and standard deviations for *tone\_1* by *level* are as follows: Level 1 ( $M = 6.65$ ,  $SD = 10.58$ ), Level 2 ( $M = 6.74$ ,  $SD = 9.19$ ), Level 3 ( $M = 8.75$ ,  $SD = 14.79$ ), Level 4 ( $M = 7.00$ ,  $SD = 12.80$ ), and Level 5 ( $M = 11.81$ ,  $SD = 21.54$ ). Regarding the use of *tone\_2* by *level*, the means and standard deviations are: Level 1 ( $M = 8.59$ ,  $SD = 10.84$ ), Level 2 ( $M = 8.61$ ,  $SD = 8.34$ ), Level 3 ( $M = 11.03$ ,  $SD = 12.92$ ), Level 4 ( $M = 9.89$ ,  $SD = 12.18$ ), and Level 5 ( $M = 11.60$ ,  $SD = 14.09$ ). These results show: a slight preference of *tone\_2* over *tone\_1*, and a great variance regarding the frequency of the use of each tone. This is observed in the number of outliers present in each box plot and was caused by participants using *tone\_1* and *tone\_2* quite differently from each other.

To assess the effect of frequency of use of the teleport ability on *success*, we fitted a model to the level one and two data using *level*, *tone\_1*, *tone\_2*, *teleport* as fixed effects and *participant* as a random effect. We found that *tone\_2* was a statistically significant predictor ( $p = 0.033$ ) but *level* ( $p = 0.070$ ), *tone\_1* ( $p = 0.337$ ) and *teleport* ( $p = 0.700$ ) were not. This suggests that the increased use of *tone\_2* may slightly improve participants' success rate if the ability to teleport is also available.

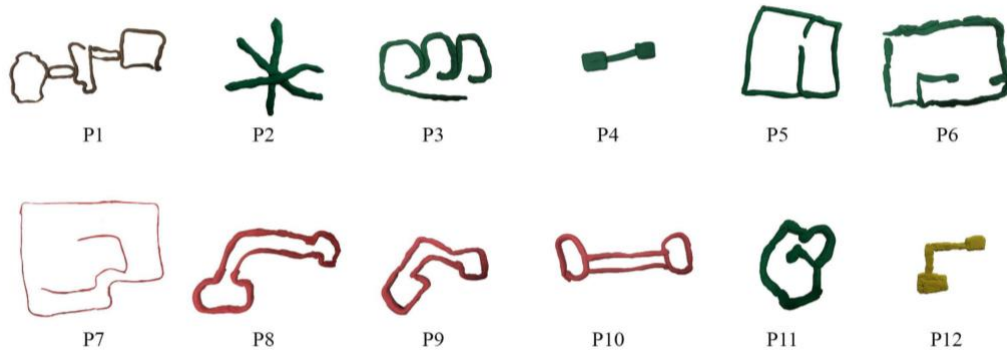


Fig. 4. Models produced by participants. Most participants identified several features of the virtual space.

**5.2.2 Qualitative results: landmark knowledge.** While exploring the role of active echolocation in the acquisition of landmark knowledge, the quantitative data from **part one** of our study suggests there was no interaction between using the artificial sound pulses and succeeding at identifying the goals of the levels of the first part of our experiment: materials, relative size of rooms, 90-degree turns, openings and obstacles.

However, our qualitative results from **part one** of our study suggest that participants relied on the echo generated by their footsteps to obtain landmark information. P2 stated that: *"I used the echo of the footsteps more... because it sounds better than the echo of the control. The echo of the footsteps was more clear."* P12, who was an expert echolocator, gave a similar explanation: *"to me it's very much [clicking sounds with tongue in the real world] are really very sharp and very short, so I found the footsteps close to that."* Similar thoughts were echoed by P4, P9 and P10.

The behaviour of obtaining information from footsteps rather than by other sound pulses matches the tactics that P7 and P12, our expert echolocators, said they would employ in the physical world. P7 said: *"the clicking sound is a weird sound that everyone wants to learn [but] I don't use it often."* P12 added: *"for me, clicking is something I do on a longer range information. The shorter range information on is there an entrance, is there a wall, all that stuff is usually just from the cane or from walking."* Therefore, footsteps may be an effective way to enable active echolocation in virtual worlds. In contrast, artificial clicks were perceived as less useful.

**5.2.3 Qualitative results: modelling survey knowledge.** In **part two** of our experiment participants completed a reconstruction task using clay to re-imagine the space that they had explored with echolocation. In this study we investigated the degree to which echolocation supported the acquisition of survey knowledge and formation of a mental map of the layout, Figure 4 shows each participant's reconstruction of the original layout (Figure 2). The reconstructions provide insight into participant's ability to use echolocation to survey a space and discern its layout. The reconstructions are a useful proxy for the participant's mental map of the original space.

In Figure 4 we can observe that P8, P9 and P12 produced accurate replicas of the virtual world, and P1 produced a reasonably accurate model, but the L-shaped corridor included unnecessary parts. All these participants' models clearly show two rooms of different size connected by an L-shaped corridor. P4 and P10 modelled two rooms of different sizes but did not model the 90-degree turn in the corridor. P5, P6 and P7 modelled two areas but no corridor, and P2 and P3 produced models that do not show any clear room.

| Feature                     | Participants |
|-----------------------------|--------------|
| Two rooms                   | 9            |
| Corridor                    | 6            |
| Corridor has an L-shape     | 4            |
| Rooms are of different size | 5            |
| Accurate models             | 6            |

Table 5. Features identified in the reconstruction models, and number of participants who identified them.

Our qualitative results suggest that participants used different techniques to describe the virtual world, including: perimeter-recognition tactics, listing elements, and describing holistic map models. For instance, 11 participants except P1 used some sort of perimeter-exploration technique that involved them walking close to, but not bumping into the virtual walls. P12 described his approach as follows: *"I'd walk from the wall and use my footsteps to hear the opening: that's exactly what I would do [in the real world], and so I would generally not spend a lot of time walking around the middle of the room."* P11 described the following reason for staying closer to the walls: *"when you are close [to a wall], you feel like the echo getting like closer. It's like if you were moved, directly, to the physical world."* Perimeter exploration strategies aligned to what participants would do in the physical world and bumping into walls was not used by our participants as a means to build a mental image of the layout of the virtual world.

Listing elements is a known technique for describing space [44]. Table 5 shows the features participants listed and the number of participants who identified these features. Participants were expected to list: two rooms and an L-shaped corridor. P8 listed these elements quite clearly: *"There were two rooms connected through a hall in an L shape."* However, other participants, such as P1, P3 and P11 listed the elements but did not describe the L-shape of the corridor. P5 and P12 also specified that the rooms were of different size when listing the elements. Participants shared different pieces of information when listing the elements that comprised the virtual space.

Not all participants successfully described the elements of the virtual space. P2 gave the following description: *"I entered at the beginning but I never found the end... [The level] had a beginning but it had no end."* For P3, the layout of the second part of our experiment was *"a cycle... I never finished looking for the beginning and the end, [even though] I entered through the corridor and looked for the exit."* These descriptions matched the participants' inaccurate models.

Regarding the description of holistic map models, P7 stated that for them the two rooms were not actually rooms, *"they were just like divisions, there weren't absolute separations."* However, other participants successfully provided a more detailed description of the layout, with P8 saying: *"The labyrinth was short on top, short on the bottom, short on the left, but on the right side it was long, long, long. And there one went to another room."* P6's description was short but accurate, even if their model showed what looked like two areas separated by a wall: *"There were two rooms of different size and they were connected to each other by a tunnel."* P3, P8, P11 and P12 provided similar descriptions, with P8 and P12 being able to provide information regarding the orientation of the features of the rooms in relation to the compass points. Several participants were able to establish a relationship between the compass points and the elements of the virtual world, giving a richer description of the layout.

### 5.3 RQ3: what are participants' opinions regarding the use of echolocation to acquire spatial knowledge of virtual space?

By replicating echolocation, a phenomenon from the physical world, the qualitative analysis of data from **part two** of our study showed that participants felt a sense of presence in the virtual world: "the subjective experience of being in one place or environment, even when one is physically situated in another" [94, p.225]. Additionally, participants felt they could improve their echolocation skills if they were exposed to the virtual world for longer periods.

Participants discussed the sense of presence they felt in the virtual space throughout both parts of the experiment. P5, P9, P11 and P12 commented they felt as though they were exploring a physical room. P9 said: *"I did feel it, like I was in a room, but an empty room."* For P1: *"when I advanced, I could notice that the place, the sound and the space varied."* P5 thought this was because *"we people who have acquired blindness... we always follow the sound, so when I enter a place... I already imagine how the room is distributed."* Moreover, P12 related this sense to their own ability to echolocate in the physical world:

*"These rooms by the end were feeling kind of real... There was different feedback than real echolocation, but by the end there was some level of training kicking in where that was making sense with the shape of the room... There was a sense like: this feels like walking across a hard floor in a room [and] the sound of the echo is changing as you approach the front wall."*

The incorporation of echolocation capabilities may enhance the sense of presence in virtual worlds.

P3, P4, P8, P10 and P12 wondered how they would improve after interacting with our system for longer periods of time: *"if you start to use a tool like this repeatedly, you will be developing training of [the auditory] sense"* (P3). Moreover, P11 stated that *"with more practice you'll be able to improve"*, and P8 added they would like *"to try different sounds, to see which ones would be more sensitive to the ear."* Participants' comments reflected the belief that their ability to use echolocation would improve over time.

### 5.4 Controller usability and perceived value to PVI

Other codes that appeared during our thematic coding of data from **part two** of our study described participants' opinions about the usability of the Xbox controller, and their' feelings about the value that interacting with a virtual world may bring to the lives of PVI.

There was agreement by all the participants that the Xbox controller was a useful tool to interact with a virtual world. P1 qualified it as *"excellent and didactic"*, P2 and P5 described it as *"very accessible."* For P3, the controller was *"very easy to handle."* P6, P4 and P11 also had positive comments on the two sticks used to control the walking and viewing directions of the virtual avatar. Even though only P8 had previous experience with a similar controller, participants' comments reflected how intuitive it was for them to use the controller.

Finally, participants described the reasons why they would be inclined to interact with a virtual world. P1 saw potential in helping explore unknown spaces: *"it's like a starting point, it helps us to be able to progress, to know where to walk."* P3 added that *"[even though] I'm not very fond of games, it seemed to me that it could be used to develop the sense of orientation."* Similar thoughts of using virtual echolocation to improve orientation and mobility skills were echoed by P5. Additionally, P2, P8, and P11 thought that the virtual world could be used for hedonic purposes. According to P2: *"it is also a relaxation when sometimes I am saturated with work, then I could go to the game."* and for P11 *"it would be super great to take the stress away."* Participants saw value in using virtual

worlds that support echolocation to improve their orientation and mobility skills, and as a means of entertainment.

## 6 DISCUSSION

We have organised the discussion around the following points: echolocation as a tool to acquire landmark knowledge and create mental maps of virtual space, and insights PVI views on digital games. To the best of our knowledge, this is the first study that describes how people with visual impairment use echolocation as an interaction technique to obtain both landmark and survey information of a virtual space, as other attempts where participants identify virtual walls, size of rooms or virtual layouts have relied on sighted individuals [23, 25, 56]. Moreover, our study complements previous feasibility studies on the use of echolocation to explore virtual worlds [3, 95].

### 6.1 Echolocation and landmark knowledge of virtual worlds

Previous experiments on echolocation in the physical world have focused on detecting the presence or specific features of objects. In these experiments, participants remained stationary while presented with an adjustable disk that contained the desired feature [37, 50, 73]. The features evaluated included: the material an object was made of [37, 40, 78], the size of an object [40, 50, 62], whether an object was moving or stationary [73, 79], and whether a collision with an obstacle was imminent [18, 75, 78]. Our study built on these previous experiments by encoding some of these features in a virtual space as landmark knowledge and evaluating participants' ability to identify them. In doing this, we have provided a novel way to evaluate the use of active echolocation to learn about landmark features of virtual space.

Both the quantitative and qualitative results obtained during the first part of our experiment revealed that PVI could successfully identify the material a room is made of, the relative size of virtual rooms, and the presence of 90-degree turns. The probabilities of success computed in Table 3 showed that participants were more likely to succeed in levels one (materials), two (size) and three (turns), with probabilities of 75%, 64% and 71% respectively. Moreover, our pairwise comparison demonstrated that success rates in levels one, two and three were significantly different from success rates in levels four and five (see Table 4). These quantitative findings suggested that levels one, two and three were easier than levels four and five. Participants' comments during the post-interview further confirmed these hypotheses. By using a mixed-methods approach [19] we have shed light on the landmark features of virtual worlds that PVI can detect through echolocation while providing results that are quantitatively significant and provide a rich explanation as to why some features are easier to perceive than others.

Active echolocation requires a person to actively produce sounds to echolocate. [8, 73]. Although participants were provided with two different clicking sounds, there was no significant observable difference on how they used both sounds, as shown in Figure 3. Furthermore, P7 and P12 argued that tongue-clicks served specific purposes, and in a virtual world, most participants agreed they acquired more information through the echo produced by footsteps, which coincides with what they would do in the real world. Replication of real-world behaviours has been observed with sighted players in Massively Multiplayer Online Role-Playing Games (MMORPGs), particularly in regards to social behaviours [96]. As people who use active echolocation tend to be self-conscious of the social situation they are in when using active sounds to echolocate [80], future research on echolocation-enabled virtual worlds could explore how PVI use active echolocation in this context.

### 6.2 Echolocation and mental maps in virtual worlds

While there is evidence that the use of echolocation correlates with better mobility in familiar and unfamiliar places in the physical world [78], and previous studies have evaluated the use of



virtual spaces and binaural sound to assist PVI in forming a mental image of a physical location [17, 32, 36, 44, 57], to the best of our knowledge this is the first study that systematically integrates and evaluates how PVI use echolocation in virtual spaces to acquire survey knowledge and form a mental map of a virtual location. The closest work to ours may be that of Dodsworth et al. [23], who have found that sighted individuals are able to perceive spatial layout of a virtual echo-acoustic space after several training sessions. However, our work is unique in that we focus on the experience of PVI. Our work reflects our belief that the best way to devise technologies that are accessible to PVI is to work together with them and learn from their lived experience [27, 68].

Previous exploratory research on echolocation in virtual worlds has highlighted the importance of scaffolding—providing aids when learning a new skill [10]—to deliver a successful experience [3, 95]. Scaffolding is a common technique in education, and has been used in the development of educational games to reach better outcomes [24, 74]. We provided scaffolding for participants to use echolocation to acquire survey knowledge by dividing our experiment in two parts and not randomizing the order in which participants traversed the five levels in the first part of the experiment. First, participants learned about landmark features that were then integrated in the construction of the virtual space used in the second part of our experiment. This scaffolding is reflected in P1, P2, P7 and others' comments about the sense of progression across levels. Further research could investigate the inclusion of other means of scaffolding, such as the inclusion of verbal and haptic feedback, as Weoff et al. [91] have found improved performance in a VR game when such scaffolding is provided.

Difficulties in evaluating the accuracy of mental maps produced by PVI include finding a suitable task and finding a non-ambiguous set of terms to describe the mental map [39, 67, 92]. We have followed an approach similar to that of previous researchers by combining our reconstruction test with follow-up interviews [1, 43, 44]. The agreement between participants' models and their descriptions suggests that this pair of tasks is an appropriate way of evaluating the creation of mental maps. However, we acknowledge that not all participants could successfully recreate the layout of the space they explored. According to Kitchin and Jacobson: "the utility of someone's knowledge is best assessed through tasks that demonstrate it in action, such as wayfinding in a complex environment" [39, p. 367]. While such assessment would be complicated, future research will greatly benefit from studying the relationship between exploring an echolocation-enabled virtual world modeled after a physical location and navigating said location.

Previous research recommends people with visual impairment constantly receive updated orientation information [21, 22]. Given the lack of additional sensory cues present in the virtual world participants had to explore (i.e. ambient sounds), we considered the inclusion of compass points as a sensible trade-off, as this information is independent of the layout of the rooms participants had to explore. The inclusion of compass points also addresses findings from previous research on echolocation in virtual worlds, where the inclusion of orientation cues was suggested [3, 95]. Additionally, although the use of indications for compass points may be seen as a confounding factor when analysing how participants formed a mental map of virtual space, it is important to remember that in the physical world echolocation is not used in isolation, but rather as an additional tool to obtain spatial information [79]. Hence our decision to provide compass-point information, given the lack of other ambient sounds.

Our results illustrated how PVI used perimeter-exploration strategies and integrated representations during the second part of the experiment. These techniques are similar to what they would use in the physical world [31, 35, 87]. The use of these techniques demonstrated how PVI integrate their set of unique skills in unfamiliar situations. By designing virtual worlds that support the unique skills of PVI, we get closer to creating experiences that are equitably accessible for sighted people and PVI [71].

### 6.3 Digital games and people with visual impairment

There is a growing interest in digital games targeted to PVI (commonly referred to as audiogames) and in improving accessibility in mainstream games [4, 38, 85]. However, for PVI, the transition from 2D to 3D graphics was an effective barrier that has prevented them from engaging with modern mainstream games [4, 85]. Embedding echolocation capabilities in 3D virtual worlds may unlock an entire new world of gaming for PVI.

Footsteps are a common fixture in modern digital games. Seminal research found a correlation between the use of footsteps and an improved sense of presence [86], and more recent research has explored the use of realistic footsteps to improve gait of participants in virtual worlds [46, 47, 54]. Despite how common footsteps are in games, this is the first work that establishes them as a tool to acquire spatial knowledge. Future research may explore why footsteps were better echolocation tools than artificial sound pulses in virtual worlds.

Even though only one of our participants had previous experience with digital games, several participants explained that they would be interested in interacting with a virtual world for relaxation purposes. It has been argued that playing games is a fundamental human desire [34] and specific tools have been designed to bring access to PVI to specific games [41, 84, 97]. However, one recurrent challenge these tools face is the sequential and non-persistent nature of sound [2, 38]. Integrating different means to use active echolocation in virtual worlds—through sound pulses, footsteps, clapping sounds or others—may help address these challenges by giving agency to the player, who will decide when and how to receive information from their surroundings.

Finally, we must draw attention to a different type of accessibility issue regarding research on game design and HCI more broadly: game development tools such as *Unity* and *SteamAudio* are of a "black box" nature. This makes scrutinising the inner workings of these tools near impossible. The need for more open and scrutable tools in HCI research has been argued for elsewhere [16]. In the case of this research, the black box nature of these tools makes it difficult for us to provide a more detailed technical description of the measures used in our experimental design. However, regarding the use of these tools to develop echolocation-enabled virtual environments, our participants' comments have provided strong evidence that the use of these tools facilitates the creation of more accessible virtual environments.

## 7 CONCLUSION

While previous research has explored how people with visual impairment (PVI) use echolocation to learn about their surroundings in the physical world, less is known about how echolocation may help PVI to learn about specific features and create a mental map of virtual spaces.

In this paper, we have described a two-part experiment that examined the usefulness of echolocation for acquiring landmark and survey knowledge of virtual spaces. In the first part of our experiment, we found that through echolocation, PVI could distinguish whether a virtual room was covered in carpet, wood or metal, identify the relative size of a virtual room, and detect the presence of 90-degree turns to the left or right on average 70% of the time. The second part of our experiment revealed that about half of our participants could successfully integrate this knowledge to form a mental map of a virtual space.

By focusing first on identifying specific features of virtual space and later on obtaining a more holistic map of the space, we provided adequate scaffolding for our participants. Moreover, the combination of a reconstruction test with post-interviews helped determine the accuracy of participants' mental map. Creating echolocation-enabled virtual worlds will improve overall accessibility of PVI to full 3D environments, will acknowledge PVI's unique set of skills, and will push towards the design of equitably accessible experiences.

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### 7.5. Discussion

The paper presented in this chapter builds on the findings from chapter six regarding the feasibility of creating virtual environments that support echolocation while additionally providing proper scaffolding and constant orientation cues. Scaffolding was provided through the inclusion of a training level and by not randomizing the order in which participants explored the different levels. Orientation cues were provided via the inclusion of voice indications when facing a compass point. Furthermore, the inclusion of a training level and the use of an Xbox Controller addressed issues around providing clear controls identified in chapter six. The usefulness of the scaffolding was confirmed as participants agreed that the first levels were perceived to be easier than the later levels. Making the decision to provide orientation cues via compass points may be perceived as a way to undermine the validity of the study. However, it was decided that compass point information provided the orientation cues people with visual impairment needed to successfully acquire spatial information without directly revealing any of the features being measured (Wu et al., 2017). Hence, the inclusion of compass point information was deemed a sensible trade-off.

Regarding the use of echolocation to detect landmark features of space, the study presented in this chapter revealed with 95% confidence that people with visual impairment successfully identified virtual materials, relative sizes of virtual rooms, and the presence of left and right turns approximately 70% of the time. Moreover, the reconstruction task revealed a high level of accuracy from most participants when recreating the layout of an echolocation-enabled virtual world. Participants admitted to trailing along the virtual walls in order to build a mental image of virtual space. However, they clarified that this behaviour matches what they would do in the physical world, and

highlighted the fact that, although they trailed along the walls, they did not bump into them because of the echolocation capabilities available in the environment. These findings comprise the first in-depth study of the potential use of echolocation to acquire spatial information in virtual worlds and demonstrate that echolocation could become a valid metaphor to convey spatial information in digital games. This may encourage the development of more equitably accessible games that offer the challenge that gamers with visual impairment seek while providing a new game mechanic.

Ten out of the twelve participants who took part in this study were recruited from Ecuador, my home country, amongst the pool of people with visual impairment I used to work with. This was done to surmount the difficulties I faced when trying to recruit participants from a sensitive group in Australia. Recruiting participants from an underrepresented group in a developing country further strengthens the critical realist position of this work, as the study presented in this paper has provided a unique opportunity for the voices of largely underrepresented groups in academic literature to be heard (Sumathipala et al., 2004). Moreover, to ensure that this work continues to be aligned with the ethical dimension of the critical realist agenda presented in chapter three, the risks for participants were reassessed and ethics requirements re-evaluated to ensure the safety of participants at all times.

Participants' comments about the potential use of echolocation-enabled virtual environments either for orientation and mobility purposes or for entertainment purposes supports the argument I made in chapter three, that research on accessibility of digital games is desirable under a critical realist lens, as games have the potential to impact the self-esteem and self-confidence of people with visual impairment. Moreover, implementation of echolocation in virtual worlds may support people with visual

impairment engaging with mainstream games without attracting any unwanted attention (van de Ven et al., 2005).

To summarise, this chapter has provided answers to **RQ3**: what features of virtual space can be revealed through echolocation? And to **RQ4**: how do the features revealed through echolocation support acquisition of spatial knowledge in virtual space? This is the first in-depth study of how echolocation may be used to learn about spatial information—via acquisition of both landmark and survey knowledge—of virtual worlds. Furthermore, according to several people with visual impairment who participated in the study presented in this chapter, implementing echolocation in virtual worlds may support their engagement with these worlds for orientation and mobility training, and for hedonic reasons. Building on the findings from this chapter, the next chapter aims to further enhance our understanding of the usefulness of echolocation in virtual worlds by learning from the lived experience of expert echolocators via a participatory design process. This process ensures that design decisions are guided by people with visual impairment. The outcome of this process is a series of design guidelines that will produce richer gaming experiences for people with visual impairment.





# Chapter 8: A Participatory Design

## Exercise on Echolocation

### 8.1. Introduction

Section III of this thesis thus far has described how to implement echolocation so that it supports the acquisition of spatial information, and it has provided an in-depth exploration of how echolocation supports the acquisition of both landmark and survey knowledge in virtual space. Although the feedback received after every interaction with participants was integrated before the next user study, it could still be argued that some of the most important design decisions were made by the researcher. To balance power more fairly in the critical realist context of this thesis, this chapter presents the results from study 3, which followed a participatory design approach. This involved partnering with expert echolocators so as to ensure that the voices of people with visual impairment are an integral part of the design process. Study 3 aims to answer **RQ5**: How can a co-creation process inform the design and implementation of echolocation in virtual spaces? Furthermore, study 2B revealed some features of virtual space that were more difficult to identify using echolocation (namely, openings and obstacles), so there was a need to further interrogate how to best design echolocation-enabled virtual spaces that support acquisition of knowledge about these kinds of spaces. A participatory design approach was suitable to conduct this interrogation because, as described in chapter three, I strongly

believe—like Shakespeare (2013) and Frauenberger (2015)—that the only way to find out what works for people with visual impairment is to ask them directly.

Critical realism as a lens to interrogate the design of accessible technologies for people with disabilities argues for valuing the knowledge and skills acquired by people with disabilities through their lived experience (Shakespeare, 2013). Participatory design focuses on democratising decision-making processes (Bannon et al., 2018) and co-learning from the experiences of participants (Robertson et al., 2014). This is particularly important when participants “provide an entirely different vantage point shaped by their social, physical, and artistic experiences” (Oswal, 2014), as is the case of people with disabilities. Hence the suitability of participatory design methods in the context of critical realist research.

The methodology used to conduct the participatory design exercise presented in this chapter was based on the methodology presented by Albouys-Perrois et al. (2018) and Metatla et al. (2015). This methodology outlines a 4-step approach to participatory design. The steps presented in the authors’ methodology are presented in Figure 4 and include: participant recruitment, an informative phase, and iterative cycles of prototype creation and evaluation. The outcome of employing this methodology were seven design recommendations that describe how to best implement echolocation in virtual worlds. Of these seven recommendations, four were implemented and tested with participants. Importantly, the preliminary evaluation of these four design ideas improved participants’ ability to detect the presence of openings and obstacles in virtual worlds.

The results obtained from the participatory design exercise conducted for this chapter were summarised in a paper called “A Participatory Design Approach to Designing Echolocation-Enabled Virtual Environments”. As of the time of this writing,

the paper has not yet been submitted, as it references the paper presented in chapter seven, whose review has been delayed due to the covid-19 pandemic of 2020. The paper presented in this chapter will be submitted to the Journal *Transactions on Accessible Computing (TACCESS)*. If accepted, the paper will be published shortly after the submission of this thesis. The version of the paper presented in this chapter is the latest available before receiving comments from reviewers.

### **8.2. How this paper contributes to the thesis**

This paper supports the critical-realist approach of this thesis by explicitly leveraging the lived experience of expert echolocators to further improve the design of echolocation-enabled virtual worlds. More specifically, this paper addresses findings from chapter seven, where participants struggled to detect the presence of openings and obstacles in virtual worlds. In this paper I provide unique design recommendations that will support the design of more equitably accessible virtual experiences and will potentially integrate echolocation as a new metaphor of interaction. Moreover, the paper presents a preliminary evaluation of key design ideas elicited from expert echolocators. Findings from this evaluation suggest that these design recommendations improve participants' ability to acquire spatial knowledge, specifically when having to detect openings or obstacles.

### **8.3. Data collection and analysis methods**

The paper presented in this chapter follows a participatory design approach, as described by Albouys-Perrois et al. (2018) and Metatla et al. (2015). A participatory design

approach supports the construction of a multi-faceted and interactional understanding of the relationship between disability and technology, while emphasizing the importance of learning from people with visual impairment in order to find what works for them (Frauenberger, 2015; Shakespeare, 2013), thus supporting the critical realist approach of this thesis.

According to the participatory design approach described by Albouys-Perrois et al. (2018) and Metatla et al. (2015), a participatory design exercise comprises: a recruitment phase, where researchers and participants reach an understanding about the goals of the project, an informative phase for preliminary elicitation of ideas, and an iterative prototyping and evaluation phase to test participants' ideas. This is shown in Figure 4. The figure shows that there were two prototyping and evaluation cycles for this participatory design exercise.



Figure 4. Participatory design process

Three expert echolocators were recruited as participants for this study. All participants have used echolocation in the physical world from early childhood, two use both active and passive echolocation and one uses passive echolocation. Before engaging in discussions about how to improve the design of echolocation-enabled virtual environments, it was crucial that participants had a strong understanding of the system designed and used in study 2B. Therefore, each participant took part in a familiarisation session in which they followed the protocol of study 2B. The goals for the session were for participants to become familiar with existing echolocation capabilities of the virtual

environment I have developed through this thesis and to familiarise themselves with the use of an Xbox controller. Furthermore, by trialling study 2B first, we could reach an understanding about the goals of this new study with participants, so that they could focus on how to improve the existing implementation of echolocation. Participants' completion of study 2B occurred months after the manuscript presented in chapter seven was finalised and sent for revision, so the results from the three expert echolocators involved in this study could not be included in study 2B.

This study relied on qualitative methods for data collection and analysis. The informative phase was conducted via a focus group session where participants discussed their lived experience of using echolocation to learn about the physical space and described possible strategies to improve the usefulness of echolocation in virtual worlds. The data recorded from the focus group were analysed using thematic analysis (Braun & Clarke, 2012). The result of this analysis led to the formulation of seven design recommendations for the creation of echolocation-enabled virtual experiences.

Of the seven design recommendations identified by participants during the focus group session, two were implemented and tested in the first evaluation phase and another two were implemented in the second evaluation phase. The design recommendations implemented were chosen by the participants and aimed to improve participants' ability to detect openings and obstacles—as these features were the most difficult to identify, according to the findings from study 2B. Also similar to study 2B was the request for participants to recreate the virtual environment they explored using modelling clay. The models were photographed and used for observational purposes, and the modelling tasks were followed by semi-structured interviews during each evaluation cycle.

#### **8.4. The paper**

A PDF file of the paper can be found at [\*\*http://go.unimelb.edu.au/r73j\*\*](http://go.unimelb.edu.au/r73j).

## A Participatory Design Approach to Designing Echolocation-Enabled Virtual Worlds

RONNY ANDRADE\*, JENNY WAYCOTT, STEVEN BAKER, and FRANK VETERE, The University of Melbourne, Australia

As virtual worlds—in the form of videogames and augmented and virtual reality experiences—become more popular, it is important to ensure that they are accessible to all. Previous research has identified echolocation as a useful interaction approach to enable people with visual impairment to access virtual worlds. In this paper, we further investigate the usefulness of echolocation to explore virtual worlds, following a participatory design approach that comprised a focus group session coupled with two fast prototyping and evaluation iterations. During the focus group session, expert echolocators produced a series of seven design guidelines, of which we implemented and trialed four. The evaluation of our implementations revealed that the use of ambient sounds, the ability to place landmarks, directional control and the ability to use pre-recorded mouth-clicks produced by expert echolocators improved the overall experience of our participants by facilitating the detection of openings and obstacles. The recommendations presented and evaluated in this paper may help to develop virtual worlds that support a broader range of users while recognising the value of the lived experience of people with disability as a source of knowledge.

CCS Concepts: • **Social and professional topics** → **People with disabilities**; • **Human-centered computing** → *Auditory feedback*; *Accessibility technologies*.

Additional Key Words and Phrases: echolocation, virtual world, participatory design

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## 1 INTRODUCTION

Digital games have become a cultural phenomenon and a multi-billion dollar industry, with an estimated 2.5 billion people playing digital games worldwide in 2019 [13, 84, 85]. Digital games rely heavily on graphics to convey information to players; this reliance is reflected in the common denomination: "videogames" [12]. However, this reliance and strong emphasis on visual content means that those who live with a visual impairment are frequently excluded from engaging with these contents [17, 18, 75]. There is, however, a strong desire on the part of people living with visual impairment to play digital games. Therefore, despite their reliance on graphics to convey information, people with visual impairment continue to develop creative strategies for engaging with such games [19, 41].

\* Corresponding author

Authors' address: Ronny Andrade, [andrader@unimelb.edu.au](mailto:andrader@unimelb.edu.au); Jenny Waycott, [jwaycott@unimelb.edu.au](mailto:jwaycott@unimelb.edu.au); Steven Baker, [steven.baker@unimelb.edu.au](mailto:steven.baker@unimelb.edu.au); Frank Vetere, [f.vetere@unimelb.edu.au](mailto:f.vetere@unimelb.edu.au), The University of Melbourne, Parkville, VIC, Australia, 3010.

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An emerging digital game market that presents unique challenges to people living with visual impairment is virtual and augmented reality (VR/AR). Recent interview-based studies have demonstrated that visually impaired gamers are excited by the potential of VR/AR, but are concerned that the affordances of these technologies are likely to further exclude them from engaging with VR/AR content [3, 83]. Given the current state of near-maturity of VR/AR, it is critical to make these technologies accessible by design, thus providing more democratic access to such technologies [10, 49].

Previous research has attempted to replicate echolocation—the use of sound and echoes produced by sound reflecting off different surfaces [38, 39]—to improve accessibility in virtual worlds for people with visual impairment [2, 5, 54, 68, 88]. Schörnich et al. [68] and Robinson & Kearney [60] have explored the use of echolocation in virtual worlds to detect obstacles and Andrade et al. [FORTHCOMING] explored how echolocation supports the formation of a mental image of a virtual space. These studies show echolocation improves the ability of people with visual impairment to engage with virtual worlds. While this earlier work has established that echolocation is a viable approach to navigating virtual worlds, more work is needed to ensure that echolocation responds to the needs of people with visual impairment. A notable omission from earlier work is any attempt to partner with people living with a visual impairment to improve the design of echolocation in virtual environments. The goal of this paper is to address this gap.

In this paper, we expand on the existing knowledge regarding the usefulness of echolocation as a means to make digital games more accessible. We follow a participatory design approach, where we obtained several design ideas from expert echolocators, implemented and evaluated some of these ideas and found that they improved participants' ability to create a mental image of the virtual space being explored. By using a participatory design approach, this research attempts to democratise access to the design process of digital games by providing a true reflection on the lives and knowledge of people with visual impairment and ensuring they have agency regarding design decisions [10].

## 2 AIM AND CONTRIBUTIONS

In this work, we aim to describe how echolocation can be best implemented in virtual worlds in order to make them more accessible to people with visual impairment by learning from expert echolocators through a participatory design exercise. Our specific contributions are:

- Presenting a series of design recommendations elicited from expert echolocators in a participatory design exercise to improve existing implementations of echolocation in virtual worlds.
- Evaluating several of these design recommendations and describing ways to further improve the implementation of echolocation-enabled virtual worlds to improve accessibility for people with visual impairment.

Although previous research has provided an initial understanding of the potential of echolocation to make virtual worlds more accessible, this is the first work in this area that follows a participatory approach to reflect and learn from the lived experiences of people with visual impairment, including their voices in the design stages of a technology solution, and therefore producing more democratic technology designs [10, 69].

## 3 PREVIOUS WORK

This work is informed by existing literature exploring echolocation as it occurs in the physical world, previous attempts to implement echolocation in virtual worlds, current trends in accessibility



in digital games for people with visual impairment, and participatory design approaches in the field of Human-Computer Interaction (HCI) to create accessible tools.

### 3.1 Echolocation

Echolocation is the ability to use sounds and their echo reverberations to create a mental image of one's surroundings [38, 39, 78]. The use of echolocation has been observed in bats, dolphins and some humans [79, 80]. According to anecdotal accounts in the literature, 20 to 30 percent of blind people can use echolocation [77]. There is a distinction between active and passive echolocation: active echolocators generate their own sounds to echolocate. In contrast, passive echolocators rely on environmental sounds to assist with navigation. [7, 73]. Sounds used by active echolocators include: sharp clicking sounds produced with their tongue, footsteps, finger snaps and claps [62].

A mental map is the internal representation a person builds of their surrounding space by combining the available stimuli present in said surroundings [36, 66]. Most people rely on visual stimuli to build a mental map of their surroundings. However, people with visual impairment must rely on other stimulus, such as tactile and auditory stimuli, as visual input is not available to them [36, 66]. Echolocation may play an important role in forming a mental map, as it has been found that people who echolocate in the physical world can detect distance of moving and stationary objects [32, 63], size of objects [46, 76], the material certain objects are made of [23, 29], the presence of obstacles [74], and report better orientation and mobility outcomes in familiar and unfamiliar spaces when compared with non-echolocators [77].

There have been attempts to implement echolocation in digital worlds: through the design of specific hardware and software solutions [58], the use of proprietary acoustic-simulation software [54, 56] or the use of free, off-the-shelf components [2, 5, 88]. These attempts have had different goals: Wu et al. [88] used pre-recorded sounds and echoes in a grid-like maze to teach people how to use echolocation; Andreasen et al. [5] argued that the use of echolocation may improve ownership over the virtual space, Neidhardt et al. [50] and Pelegrin et al. [54] used their implementation of echolocation to find out whether participants could identify a virtual wall and orient themselves towards it. Andrade et al. [FORTHCOMING] argued that echolocation may assist people with visual impairment in acquiring spatial information and forming a mental map of virtual space.

Although this prior work demonstrates there is clear interest in using echolocation as a means to make virtual worlds more accessible, our participatory design approach is the first to include expert echolocators in the design stage of an echolocation-enabled virtual world.

### 3.2 Accessibility in digital games for people with visual impairment

Previous approaches to accessibility in digital games for people with visual impairment have been limited to the introduction of a specific game and its subsequent evaluation, delivering what is known as *artifact* contributions [15, 87]. Although some of these artifacts are still enjoyed by people with visual impairment—such as the audiogames *Swamp* [6] or *AudioQuake* [8], a more general approach to understanding the needs of people with visual impairment is needed to develop more accessible games.

**3.2.1 Audiogames.** Audiogames are a type of digital game designed for people with visual impairment. These games provide a completely auditory experience, where all the elements of the gaming experience are presented through sound; these games may have minimal or no graphics [25]. Kirke [35] provides a detailed summary of these types of game, and the website [www.audiogames.net](http://www.audiogames.net) provides a library of more than 500 titles ranging from trivia and educational, through to racing and RPGs (role-playing games).

Although audiogames provide a source of enjoyment and a means to engage with the broader cultural phenomenon of gaming, gamers with visual impairment have argued that many audiogames are rather simplistic and offer low replayability value [3, 83]. Moreover, Kirke [35] highlights the sequential nature of sound as a potential problem when designing audiogames. A common example of the simplistic approach present in audiogames is in the way space is represented; several audiogames use a grid-like system that limits the players' ability to move in the game to four pre-established directions: North, South, East and West [4, 26]. This is in contrast to modern mainstream videogames, where sighted players control a character that moves in any direction in a virtual environment.

Another challenge associated with the development of audiogames is designing meaningful affordances. An affordance communicates potential behaviours to users in relation to what can be done in-game [52]. Unlike videogames, audiogames cannot rely on visuals to communicate available actions to players. Furthermore, Norman [51] warns against using overly literal metaphors, as these may obscure the potential for action. Audiogames should balance the use of affordances that are easy to discover and that prioritise usefulness over real-world fidelity.

**3.2.2 Beyond audiogames.** There have been attempts to provide a broader understanding of the relationship between gamers with visual impairment and digital games. The work of Andrade et al. [3], and Urbanek & Güldenpfennig [83] provided an insight into the habits, opinions and concerns of gamers with visual impairment. Gamers with visual impairment have expressed fears of being left behind as VR/AR experiences become more commonplace. Furthermore, Andrade et al. [4] have proposed a framework for making games more accessible, where providing mechanisms for gamers with visual impairment to understand the virtual spaces where a game takes place is of critical importance.

As digital games, VR and AR experiences become more commonplace, it is necessary to develop mechanisms for these experiences to be accessible by design—instead of retrofitting accessibility features, these should be included by default in the design process [49]. Works such as that of Zhao et al. [90], who have developed a tool that provides a series of visual and audio augmentations to make VR more accessible to people with low vision, and Andrade et al. [FORTHCOMING] who argue for the use of echolocation to convey spatial information in virtual space, provide initial examples on how new tools could help deliver digital experiences that are accessible by default. However, it is necessary to ensure that these approaches to accessibility are developed in consultation with the target population to ensure that the unique perspective and skills of people with visual impairment are leveraged as a source of knowledge, thus ensuring the voices of people with visual impairment are part of the design process [10, 53]. We argue that participatory design is key to achieve this.

### 3.3 Participatory design in HCI and disability

Development of some technologies for people with disabilities, including visual impairment, has previously been based on the medical understanding of disability and followed a deficit-driven approach. Under this approach, the role of technology is to compensate for or "normalise" the situation of the person with a disability [40, 43, 61, 89]. Since excluding people with disabilities from the design process of technologies meant to be used by them is one of the reasons why they abandon these technologies [55, 89], it is necessary to find approaches that move away from this deficit-driven approach and include people with disabilities in the design process. The inclusive nature of participatory design supports moving away from this rhetoric of "normalisation".

Participatory design is a methodology that originated in Scandinavian countries in the sixties and seventies. It was initially denominated "cooperative design" and emphasised collaboration

between designers and users, recognising the need of both groups to learn together and from each other [28, 59]. According to Robertson et al. [59]: "designers learn from participants about their experiences, practices and situations, and participants learn from the designers about potential technological options". Moreover, participatory design followed a Socialist/Marxist tradition that sought to empower people who are commonly excluded from decision making with respect to technology [10]. In the context of technology design for people with visual impairment, the use of participatory design provides designers and researchers with a new appreciation of the unique skills that people with visual impairments develop through their lived experiences, and may give agency to people with visual impairments by involving them in the design process [44, 53].

Participatory approaches provide a more holistic understanding of the relationship between technology and disability [24, 69]. By using a variety of methods such as observation, focus groups, technology probes, and others, participatory design provides a means to learn from and reflect on the experiences of people with disabilities [10, 28]. By recognising that people with visual impairment are "expert in their experience" [30], participatory design aims to balance power between designers and users.

Albouys et al. [1] and Metatla et al. [44] have suggested different phases to the process of participatory design, including: establishing an understanding of outcomes with participants, generation of ideas, and iterative prototyping and evaluation. Moreover, Metatla et al. [44] have used a combination of initial workshops to generate ideas and participatory prototyping. Our methods have been informed by the four steps noted in Figure 1, with the use of a focus group session to elicit ideas, and two subsequent prototyping and evaluation stages.

## 4 METHODS

This study consisted of four stages: recruitment, generation of ideas, and two iterations of prototyping and evaluation, as shown in Figure 1. During the first stage, we contacted three expert echolocators who have interacted with an echolocation-enabled virtual environment before. Through a focus group session, we aimed to learn from participants how their lived experience as expert echolocators may inform the design of echolocation so that it is more usable in virtual worlds. The focus groups elicited seven design recommendations and the participants then played an active role in helping us to prioritise, prototype and evaluate four recommendations. A first evaluation session took place two weeks after the initial focus group session. In this session, we tested two of the four design recommendations that we decided to implement—labelled "Ambient sounds" and "Coin landmarks" in Figure 1. Finally, two weeks after the first evaluation session a second evaluation session occurred. In this second session, we tested two different design recommendations—labelled "Pre-recorded sounds" and "Directionality" in Figure 1. These evaluations sought to validate some of the design recommendations that had been elicited during the focus group session. In total, this study was conducted over a period of six weeks in the months of November and December of 2019 and it was approved by the University Ethics Committee, ethics ID 1749810. Participants received a financial compensation of \$40 Australian dollars for approximately 4.5 hours of participation.

### 4.1 Participants—Establishing an understanding

We started our participatory design exercise by recruiting participants and collaboratively establishing an understanding about the aim of the project [1]. Participant recruitment is a key stage of a participatory design process, as the aim of the process is to ensure that "users' needs and expectations are being expressed" [40]. To ensure this, participants were recruited via convenience sampling. In order to reach an understanding about the goals of the project, participants were required to follow the experimental protocol outlined in our previous research first [FORTHCOMING]. The goal of this was to ensure participants were familiar with the capabilities of echolocation-enabled

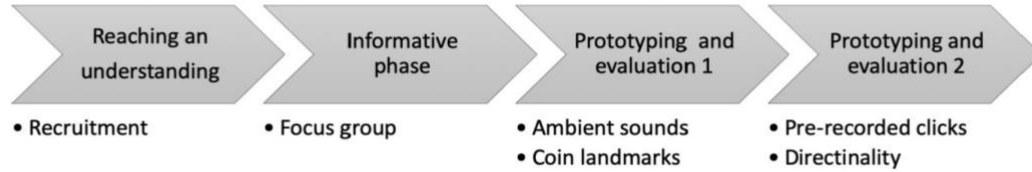


Fig. 1. Steps followed in our participatory design study

virtual environments so that the discussion could focus on improving the existing implementation. Furthermore, convenience sampling enabled us to work with three expert echolocators. Upon individual conversations with potential participants, it was established that the goal of the present study would be *to explore ways to improve current implementations of echolocation in virtual worlds to make them more accessible*. Table 1 shows demographic information of our participants, including: the pseudonym they will be referred by in this paper, their age range, the type of echolocation they used, their gender and their self-reported level of remaining vision. All our participants have developed their current level of vision from early childhood.

Cari and Rob relied on a white cane for mobility all the time, while Ken relied on the white cane only sometimes. Rob preferred to use a clicking sound produced with his mouth to echolocate, Cari used a finger snap and Ken relied on environmental sound sources and the echo these sources provided. Although Ken used passive echolocation only, we found his experience as a passive echolocator and professional experience as a sound engineer of value for our project. Moreover, further conversations with participants, described below, highlighted the importance of passive echolocation for all echolocators. This is something that existing literature has not explored.

Although a sample size of three may seem small, determining an adequate sample size in a qualitative study depends on the quality of the information collected, the particular research method, and the outcome intended [67]. Moreover, studies like ours—where the goal is to further explore a novel interaction technique—benefit from gathering in-depth opinions from participants rather than from large sample sizes [14, 37]. Additionally, working with a very specific group of participants who provide rich insights in the topic being explored leads to the collection of powerful insights, despite the small sample size [42]. Thus, a sample size of three is justified by the fact that our participants were expert echolocators who had interacted with an echolocation-enabled virtual world previously.

## 4.2 Generation of ideas

This stage consisted on a two-hour focus group session with our three participants. As described in the previous section, the aim of the focus group session was to describe ways to improve an existing implementation of echolocation in virtual worlds to make them more accessible. This was done by asking participants to reflect on how they use echolocation in the physical world. These reflections led to the elicitation of a series of design recommendations to improve the usefulness of echolocation in virtual worlds. Particularly, the recommendations elicited aimed to support the formation of a mental map of the space being explored. The session was led by the first author, who has a lived experience of visual impairment. The session was audio recorded and the questions that guided this session can be found in the Appendix A.1. Upon completion of the focus group session, we proceeded to transcribe the audio recordings and obtained a total of 30 pages and around 12,000 words of transcribed material.

Table 1. Demographic information of participants.

| Name | Age range | Echolocation       | Gender | Remaining vision   |
|------|-----------|--------------------|--------|--------------------|
| Ken  | 35 to 45  | Passive            | Male   | Low vision: 6/18   |
| Rob  | 55 to 65  | Active and passive | Male   | Complete blindness |
| Cari | 25 to 35  | Active and passive | Female | Four percent       |

Once the interviews were transcribed, we used thematic coding to analyse our qualitative data [27]. To follow this approach, the lead researcher began by reading and re-reading the content of the transcribed interviews. He then labelled passages of text referring to similar ideas or concepts and grouped these passages into codes. A data-driven open coding approach was employed, where the researcher did not start with a pre-established set of codes, but rather identified codes as they appeared in the data. Each code then received a name and a definition. Finally, all the codes were grouped into a series of overarching themes. Each code became a design recommendation made by our participants.

Although participants were not directly involved in the coding of the themes identified from the interviews, at the end of the focus group session they, together with the lead author, summarised the contents of the session and communicated what ideas, in their opinion, had been most salient and had more potential to improve echolocation in virtual worlds. The following sections describe the design recommendations elicited from participants.

**4.2.1 Use sounds that are sharp, short and familiar.** Participants started by describing the sounds they used daily to echolocate. Cari explained she used *"cane and footsteps particularly but I also snap fingers on the other hand and find that those are very useful"*. Similarly, for Rob *"I do passive most of the time. That's the most common thing I will use. [However,] I'm a clicker<sup>1</sup>, because I usually have something in my other hand. [The] cane, for me, is much shorter range as it is a little low, so you do not get as much detail"*. Our participants' comments suggested that cane and footsteps may be common sounds used by echolocators.

Rob provides insights on what makes a good sound for echolocators. He said: *"For me, the sharper the better... I think I must have learned early to make the sharpest possible, and it must be terribly disruptive, click of the tongue that I can possibly make, to get as much of an echo as possible"*. Similarly, Cari explained that *"a very sharp finger click is what I like. I prefer to wear leather-soled shoes for exactly that reason"*. Participants, particularly Ken, helped clarify that "sharp" refers to sounds *"with the highest frequency, the most attack and the shortest"*. Participants agreed that a sharp and short click is best for echolocation.

When asked what would be the perfect echolocating sound in a virtual world, Rob replied *"the ones I already use... I reckon I am probably tuned to [my own clicking sound] and decades of experience. It is possibly the sound your brain is most used to"*. Cari thought that using her own finger snap *"would provide the more natural feedback"*. Providing sounds that are familiar, including an echolocator's own clicking sound, may improve the usefulness of echolocation in virtual worlds.

**4.2.2 Provide opportunities for passive echolocation.** Our participants described the use of passive echolocation. For Rob: *"I would just use the sound that's around [me] a lot too... I can just hear walls from the sounds that [are] around in the room"*. For Cari *"the idea of passive echolocation is fascinating... If I have to find a doorway, What [sound] are you using to do that? Well, the footstep but also that dull lack of sound you are actually looking for"*. For Ken, passive echolocation was

<sup>1</sup>Rob refers to his preference of using a sharp short clicking sound produced with his tongue and palate



important *"just to see how the room sounds"*. Listening to echo reverberations from environmental sounds helped people with visual impairment obtain information about their surroundings.

The context was important when choosing to use active or passive echolocation. For Cari: *"outdoors you use passive [echolocation] lots more... I use it to know what information I am not going to get and what is safe, what is not safe"*, whereas for Rob the opposite was true. He explained that *"I think that I use active [echolocation] outside more... Because, often, inside I am avoiding things, outside I am actively looking for them. And to find an object in an open field I have to use more volume... But then, if I am following a fence line along, just every day walking, that is almost entirely passive. And the cane is almost enough. If I click at that point it is because I got scared"*. Although each participant used passive echolocation differently, its importance is clear. Additionally, participants have explained how echolocation—be it active or passive—gave them a sense of security.

**4.2.3 Do not expect echolocation in virtual worlds to be the same as echolocation in the physical world.** Participants had trialled an echolocation-enabled virtual environment that provided the following auditory feedback: footstep sounds as the virtual avatar they controlled moved around the environment, artificial clicking sounds synthesised from data collected by [80], and voice messages indicating when the virtual avatar was facing a compass point. When asked how participants' previous experience with the echolocation-enabled virtual world described by Andrade et al. [FORTHCOMING] compared to echolocation in the physical world, participants highlighted several differences. Cari explained: *"I think the thing that did not compare, to me, to lived experience... What was really difficult was actually the North, South, East, West, because I am, directionally, quite challenged"*. For Ken, the difference fell on the nature of the software itself: *"I am wondering if the artificial nature of the software, the simulation, I wonder if that might hinder the potential... because it is software based it might make things a bit more difficult for me or anyone else"*. Rob explained that he overcame the differences over time: *"It is almost as if it is not quite the way I would do it, but I have got the clue, I know how this is fitting together. I think it is probably like any other sensory training thing. It just takes time to get used to it"*. Rob explained other ways in which echolocation in a digital world differs from echolocation in the physical world as follows:

*"You are not going to mimic the lived experience exactly and things like turning your head and stuff. I was noticing on the way down [participant refers to the way down from his office to the location where the focus group was conducted] how directionally I listen when I'm echolocating. If I'm looking for a door on the right and I walk into a pole on my left because I was not listening for it. And that is really hard to simulate. I do not even know what I am doing. Is that brain? Is my head position changing slightly?"*

Rob, Cari and Ken agreed that, despite how different echolocation in the virtual world was, it was possible to learn it. For Rob *"there is stuff around simulation that I suspect is probably really hard to capture but, given that, I also suspect that you can train yourself into the virtual world quite well"*. Cari added that *"By the end of it you see a world. It is like learning a code"*. Participants' comments suggested that echolocation did not have to mimic the real world accurately to be useful.

**4.2.4 Support directionality of the clicking sound.** Participants explained that the directionality of the sound used for echolocation is important. This is reflected in Rob's quote in the previous section referring to *"turning your head and stuff"*. Ken proposed a more complex approach to directionality, using the metaphor of *"an acoustic gun"*. For Cari, this idea would be something like *"a sniper range and you can work out what you are listening for, where you are aiming at and things"*. Rob added that this acoustic gun would *"just had 30% of the [visual] field, or a few degrees of field"*. Participants' idea of an "acoustic gun" with a narrow angle of action is distinct from echolocation in the physical

world, where the sounds produced to echolocate spread evenly in all directions. Furthermore, this idea could be implemented in virtual environments to improve precision.

**4.2.5 Provide sounds with different textures.** Participants described how echolocation helped them build a "library of textures". Cari explained that *"I think I use a lot of synesthetic<sup>2</sup> material that my brain is obviously supplying... I build up a picture of objects and textures and, for me, colors and it is completely spacial"*. Ken elaborated on this as follows:

*"That is similar to me. I am also synesthetic as well. And, for me, the colour I am perceiving, or the texture, is directly related to the frequency. So, like, a sharp click, I can sense that bouncing off something a lot better than if it was a lower, denser sound. Also, the bounce back, the echo, the reverb, also have their own separate texture or colour as well".*

For the creation of these textures, Ken suggested that *"What I would be interested to do would be to get an acoustic engineer and actually do some acoustic profiling. They have machines that shoot out white noise and record that back and look at the spectrum that comes back into the recording. And they can figure out the absorbency of various rooms and things like that"*. Moreover, Cari described the advantage of providing different sound textures: *"you could play with completely other type textures. You know, like vegetation, gravel, there are things that get picked on that give interesting landmarks as well"*. Participants' comments reflected the importance of providing a rich set of sounds that may be informed from real-world texture sounds.

**4.2.6 Facilitate inclusion of landmarks.** When asked how echolocation helped them navigate the physical world, Cari explained that *"It's certainly landmarks, auditory landmarks, so you can have a sense of the progression of where you're traveling"*. Similarly, Rob described that, while walking on familiar locations, *"my route is just landmark, landmark, landmark, done"*. Cari mentioned *"open doors, carpeted walls"* as *"wonderfully good landmarks"*. For Rob, these auditory landmarks included *"fences, long walls, gates, hedges"*. For Ken, *"[the landmark] I look for [is] always the walls first"*. Auditory landmarks helped people with visual impairment negotiate their surroundings, and the "sound texture" of materials such as fences, walls, carpets or hedges helped them establish these landmarks.

**4.2.7 External factors affect echolocating skills.** Participants explained how external factors affect their echolocating capabilities. Rob explained that when he echolocated *"I cannot talk to someone and walk unless I'm walking side by side [holding their shoulder]... I'm absolutely in a bubble"*. Cari coincided. For her *"I find it quite anxiety provoking because I find it then difficult to switch my attention safely"*. Another factor that affected our participants' echolocating skills is weather. They explained that with wet roads on rainy days *"the echolocation is gone"*. Strong winds and snow also affected echolocation.

### 4.3 Design decisions

After identifying the design recommendations outlined above, we proceeded to choose the four that, in the participants' opinion, would have the biggest impact in the overall experience of using echolocation to explore virtual spaces. Participants helped define what aspects to prioritise at the end of the focus group session. We limited ourselves to four recommendations due to constraints associated with this project and participants' own availability to attend evaluation sessions. Our evaluation focused on the subjective experience of using echolocation in virtual worlds. We took the following design decisions regarding what recommendations to implement:

<sup>2</sup>synesthesia is the condition where the brain either replaces one sensory stimulus with other, or provides two stimuli for the same sensorial input. People with synesthesia often report to "see sounds" or "hear colours"

- (1) Reflecting on participants' stated importance of passive echolocation, (section 4.2.2 and 4.2.5), we included ventilation fans as ambient sounds.
- (2) To facilitate the inclusion of landmarks (section 4.2.6), we decided to include the ability to drop "virtual coins" that would act as a way of marking out landmarks.
- (3) To support directionality of the sound (section 4.2.4)—albeit not in the form of the acoustic gun described by participants—we took advantage of the input interface to be used in the prototype evaluations by mapping a compass direction to physical buttons.
- (4) To provide sounds that are familiar (section 4.2.1), we pre-recorded participants' preferred echolocating sound and imported this sound into the prototype.

While participants helped co-design these four decisions, the choice of sounds—ventilation fans, coins, et cetera—fell on the researchers. We conducted two separate evaluation sessions. The first session tested the first two design decisions, and the second session tested the remaining design decisions. There was a gap of two weeks between each session. Figure 1 shows this process.

#### 4.4 Prototyping

Previous exercises on participatory design with people with visual impairment have suggested the use of low fidelity, tactile materials [1, 44, 45]. However, the nature of this research encouraged us to use fast, iterative high-fidelity prototyping, where we implemented some of the design recommendations identified in previous sections. We created two prototypes evaluated in two separate sessions. This section details some general design considerations that informed the design of these prototypes.

The prototypes used in this study were developed using Unity version 2018.3 and the SteamAudio version 2 beta 10 plug-in. SteamAudio provided support for real-time sound reflection and occlusion effects. Participants interacted with the prototypes through an avatar included with the Unity Standard Assets package. The avatar provided a first-person perspective of the virtual world. Participants used Audio Technica ATH-M40x headphones and an Xbox controller to interact with the digital world. The controls offered on each evaluation session varied. See Figure 3 and Figure 4 to see the controller scheme on every evaluation session. Figure 3 and Figure 4 also show the layout of the prototypes tested by participants on each evaluation session. The layouts were mirrored images of each other. This was done intentionally to reduce prototyping time and give participants a familiar yet distinct layout to explore each time.

The virtual avatar used in our experiment produced footstep sounds as participants walked in the virtual layout. Additionally, we implemented artificial clicking sounds for participants to use for echolocating. These clicking sounds were based on Thaler et al.'s research [80]. Thaler et al.'s research provided samples from expert echolocators and Matlab code to turn these samples into synthetic sounds. However, in the final stage of the evaluation of the second prototype, the artificial sounds were replaced with pre-recorded sounds from an expert echolocator (more detail provided on following sessions).

Although the SteamAudio plug-in provided high-quality material-based simulation of sound reflection and absorption—a feature that is key to simulating echolocation, one of its limitations is the use of a generic head-related transfer function (HRTF)—a function that describes how sound reaches the left and right ears differently and that is dependent on the anatomy of each individual. However, previous research has found little difference in performance when using a series of different HRTFs with participants [57], and participants in previous studies have proved to be able to identify the required stimulus despite the use generic HRTFs [2, 5, 88]. This evidence suggests that using a generic HRTF does not affect the goal of our study.



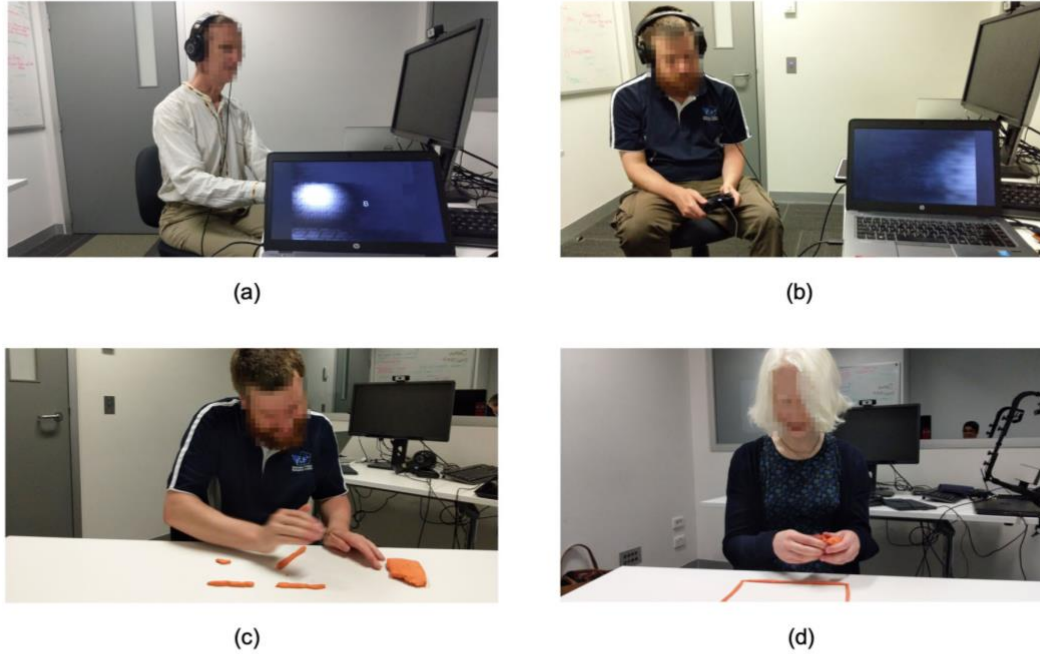


Fig. 2. Rob and Ken exploring the virtual layouts (a), (b). Ken and Cari performing the reconstruction tasks (c), (d). Participants' faces have been blurred to protect their privacy

**4.4.1 Obtaining pre-recorded clicking sounds.** To address design decision (4), it was necessary to record our participants' preferred echolocating sounds. Our three participants met us one week after the first evaluation session to assist with the recording. The recordings were made at the Horwood Recording Studio at the University of Melbourne. The studio provided an acoustically treated space optimised for the recording of vocals and offered the following equipment: Charter Oak E700 condenser microphones, Aphex 1100 mkII dual valve pre amps and BSS DPR-402 Dual Compressor/De-Esser/Limiter<sup>3</sup>. Participants were excited to be in an acoustically treated environment for the first time, and with their help we obtained an individual tongue-clicking sample and a cluster of three tongue-clicking sounds from Rob, as this is how he would use his clicking sound in the physical world. We were unsuccessful in obtaining a sample from Cari's finger snap. However, we obtained a sample of her tapping her cane on a hard metallic surface. These sounds were chosen because they were participants' preferred echolocating sounds, as described during the focus group session.

**4.4.2 Mapping commands to the Xbox controller.** Another important consideration during the prototyping stage was regarding the necessary commands and their bindings to the Xbox controller buttons. All participants had interacted with an Xbox controller at least once before, so we built on that familiarity to change the commands available to participants on each evaluation session. Each session had two parts and the commands available to participants changed on each part of each evaluation, as seen in Figure 3 and Figure 4.

<sup>3</sup>For more information on the Horwood Recording Studio, visit <http://go.unimelb.edu.au/me7x>

We used the left joystick to control the virtual avatar's walking direction and the right joystick to control the direction of the first-person camera for both evaluation sessions. During the first evaluation session, we used the A and Y buttons to produce the artificial clicking sounds synthesised from the experimental data and Matlab code provided by Thaler et al. [80], and the X button allowed participants to go back to the point of origin. When evaluating design decision (2), we bound the command to place coins to the B button of the Xbox controller. All this is presented in Figure 3.

As the second evaluation stage involved mapping compass points to specific buttons, the mapping of the commands on the Xbox controller changed substantially. The left and right joysticks kept their functionality, but the Y, A, B, X buttons were mapped to move the avatar's viewing direction to the North, South, East or West. When evaluating design decision (3) the artificial clicking sounds were moved to the top left and right triggers, as seen on Figure 4. When evaluating design decision (4), we kept the mapping of the compass points, removed the artificial clicking sounds, and used the top left trigger to produce a single pre-recorded clicking sound and the right trigger to use a burst of three pre-recorded clicking sounds. Moreover, when pressing down on either the left or right joystick—which can also act as buttons—participants would hear the recordings from Cari's cane sound, as shown in Figure 4.

#### 4.5 Evaluation

The focus group session highlighted the importance of echolocation for navigating the physical world. This inspired us to design an evaluation task that enabled participants to use echolocation meaningfully in the virtual world. We decided to ask participants to perform a reconstruction task, as described by Kitchin & Jacobson [36]. For this task, participants were left to explore a virtual space for as long as they needed to acquire a mental image of the layout of the space being explored, then they were asked to recreate the layout of the space using modelling clay. A similar reconstruction task was included in a previous study we conducted [FORTHCOMING], and participants were familiar with it.

Each evaluation session lasted 90 minutes. In each session participants explored the layout presented in Figure 3 for the first evaluation session, and Figure 4 for the second evaluation. Participants explored each layout twice, testing a different design recommendation each time. Participants were not told they were exploring the same layout twice, so they had to discover that by themselves. After finishing with the exploration, participants replicated the layout of the virtual space explored using modelling clay and took part in a semi-structured post-interview where they were invited to reflect on the usefulness of the different design decisions being tested. Questions for the post-interview during the each evaluation session can be found in Appendix A.2 and Appendix A.3. Unlike the focus group session, each evaluation session was conducted individually and there was a gap of fourteen days between the first and second evaluation sessions for each participant. Figure 2 shows participants performing both the exploration and reconstruction tasks during one of the evaluation sessions.

### 5 FIRST EVALUATION SESSION

In this evaluation, participants explored the virtual layout shown in Figure 3 twice. Figure 3 shows the initial position of the virtual avatar in the South-centre of the layout. The first time participants explored the layout, it included the sounds of fixed ventilation fans placed in the positions indicated in Figure 3. This was to address the implementation of design decision (1). The second time participants explored the virtual space, the ambient sounds were removed but participants could use the B button on the Xbox controller to place a sound landmark, as shown in Figure 3 (b). This was to address design decision (2). The sound effect chosen for this landmark was that of a coin being dropped and participants could hear the sound of coins clicking if they

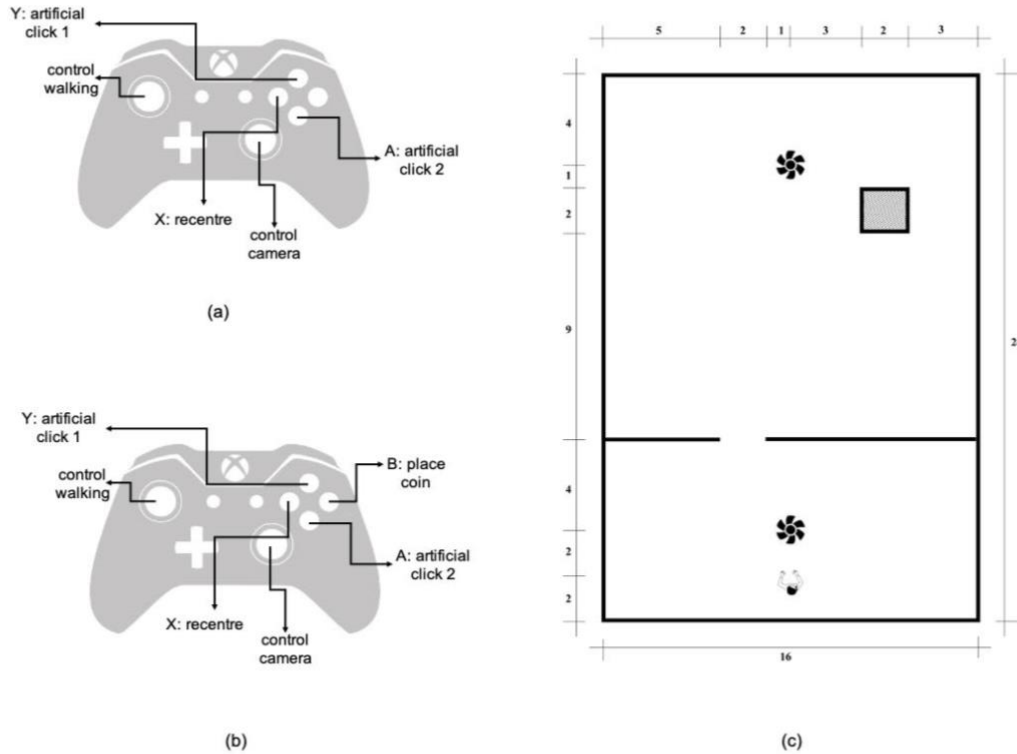


Fig. 3. Controller and layout for the first evaluation. Controller scheme used during the evaluation of the first design decision (a), the second design decision (b), and the layout used to test both decisions (c)

walked past the coin after dropping it. Both the ventilation fan and coin sounds were available in the public domain. The following sub-sections present participants' reflections on the use of these two design decisions.

### 5.1 Ambient noise

Participants explained how the ventilation sounds provided unexpected landmarks and helped detect the opening in the layout. However, these sounds were also deemed distracting. The following sections explore participants' comments in more depth.

**5.1.1 Landmarks.** Participants found the sound produced by the ventilation fans to be useful landmarks. According to Ken, when comparing the condition with ventilation fans and the condition without ventilation fans but with coins as landmarks: *"The first time I tried to explore [the layout], unless I was clicking or making footsteps, there was no way to tell where you are. So I think the good part with the ventilation fan is it provides you with a fixed reference point"*. For Rob *"the fans also changed in volume, [so their] location became more apparent... that's quite realistic"*. Cari had similar comments: *"The fan in the first one gives you a little bit of a sense of where it's situated in that room. But that doesn't tell you too much"*. Our participants agreed that ambient sounds such as ventilation fans provided fixed reference points.

**5.1.2 Detecting openings.** Apart from providing fixed reference points, the reflection of the ventilation fans made it easier for participants to identify the opening that connected the two chambers shown in Figure 3 (c). Cari explained that when standing in front of the opening, *"it's a bit more of a 'whoosh' sound... [The] reflection gives you some information about the cavities, like the cavernous-ness of the space"*. For Rob, *"the reflection from the walls also sounded like it was very closed in, which is exactly what should happen"*. Reflections of ambient sounds helped participants identify openings.

**5.1.3 Distracting.** The biggest criticism participants had for our implementation of ventilation fans was that they could be distracting. For Cari, *"it's an auditory overload of some kind"*. She stated that *"when you've got the noise going constantly, I feel anxious that I'm missing something in the real world"*. Rob added: *"the ambient sound is loud enough that it's masking some of the effect of the clicks"*. Considering the ventilation fans provided good reference points, Ken stated that *"it's a Catch-22. It's more distracting, but it's kind of helping at the same time"*. Participants have made it clear it is important not to overload the auditory channel with distracting sounds.

**5.1.4 Changes on the fly.** To respond to participants' comments regarding how distracting the fan sounds could be and in line with the participatory design approach of this study, we changed the level of volume of the fans on the fly. After reducing the fan's volume from 1 to 0.75, Rob said: *"I can certainly hear more of the clicking now the fans are a bit quieter... I reckon I'm getting clearer signals"*. For Cari, we reduced the volume of the fans to 0.75, then to 0.5, and at that point she was *"getting much more echo"*. Participants agreed that lower volume for ambient noises was appreciated, but the specific volume level changed by participant.

## 5.2 Coin landmarks

For the second part of the first evaluation stage, participants had to explore the same layout and had the ability to place coins, as described above, with the B button of the Xbox controller. Participants agreed that the idea of the landmarks was interesting, but its implementation could be improved.

**5.2.1 Small radius.** The most frequent comment regarding the implementation of coins as landmarks was that the radius for activating them was small. Ken stated that *"[it's like] trying to find a needle in a haystack... once you place them, you don't know where they are"*. Rob commented that *"it's an interesting landmark... They'd be quite useful but they probably have to be bigger than that"*. Similarly, Cari suggested that if *"you [could] hear them if you were two steps either side"*, they would be a more useful landmark. Although participants found the idea of being able to place markers to indicate landmarks interesting, our implementation did not meet their needs.

## 6 SECOND EVALUATION SESSION

The second evaluation session took place two weeks after the first session. In this session, participants explored the layout shown in Figure 4 twice. During their first exploration, participants could use the buttons on the Xbox controller to point the virtual avatar in any of the four compass directions. During the second time, apart from having the ability to face specific compass points, participants could use Rob's pre-recorded clicking sounds and Cari's cane sounds, as shown in 4 (b). These implementations were a response to design decisions (3) and (4). The following sub-sections show participants' reflections on the use of pre-recorded sounds and the ability to have more precise control over the viewing direction of the avatar.



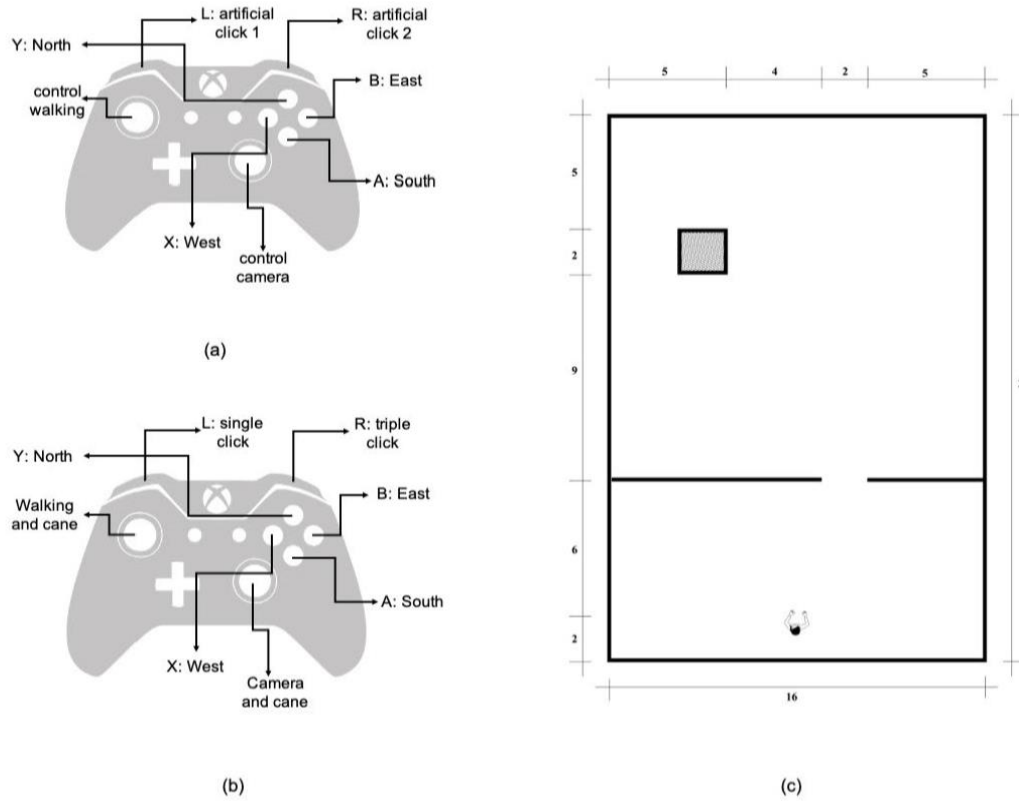


Fig. 4. Controller and layout for the second evaluation. Controller scheme used during the evaluation of the third design decision (a), the fourth design decision (b), and the layout used to test both design decisions

## 6.1 Fixed compass points

According to our participants, the changes made to the mapping of the buttons of the Xbox controllers did not affect the experience negatively, and the binding of the compass points to specific buttons facilitated the creation of a mental image of the virtual space being explored.

**6.1.1 Controller mapping.** Participants found the new mapping of the buttons to compass points easy to understand. According to Rob, the mapping *"is exactly what I'd expect"*. Ken explained how this mapping felt natural: *"as I've got the controller in front of me, North is straight ahead, South is behind me and then East and West are left and right"*. Cari added that *"because of the way we're all brought up to know about a compass being a four point, so then it sort of gives you a mnemonic, almost"*. The position of the buttons in the Xbox controller provided a natural mapping that aligned with participants' mental model of a compass.

**6.1.2 Positive impact on mental mapping.** The new mapping of the compass points provided in our second evaluation supported participants' ability to form a mental image of the space being explored. During the previous evaluation session, Ken mentioned that *"in my mind's eye I think I'm facing North where really I'm facing a few degrees off"*. The introduction of the new bindings for compass points solved this. For Ken: *"it was great, because when you select a specific direction, you*

know that that's going to be definitely the way you go". For Rob, *"I could form an absolute map of the... Okay, this is North, this is South. I know which direction I'm facing. I can put together a model map in my head"*. Moreover, when asked if they would like to use a grid-like navigation system, as used in other audiogames [4, 26], Rob explained that *"I would find it more confusing. I reckon my brain would be out there trying to construct the graph square by square"*. The use of specific compass points solved an orientation problem and supported participants in the formation of an image of their surroundings without restricting their movement across the virtual world.

## 6.2 Using pre-recorded sounds

The use of Rob's pre-recorded clicking sound and Cari's cane sound was received positively. The following sections explain why that is the case.

**6.2.1 Clicking sounds.** Participants explained how using a pre-recorded mouth-click became easier over time. Ken explained it as follows:

*"Initially, I said I didn't like the recorded click. I think the difference is because the artificial click is a lot more exaggerated high end [of the sound spectrum]. And it doesn't sound natural obviously, but I think with the recorded click, even though there's less high end information, because it's a natural sound it seemed to sound a bit more natural when it was being rebounded back... The good thing about the recorded click is that the attack is so quick and it's such a very short sound [that] the reflections are really noticeable."*

Rob also found his own recorded click useful. According to him: *"I found the actual click more useful than the artificial click. It's still just the sharper sound I was getting more information, [and also] the recorded click sounded a bit more familiar"*. Cari felt the same way. She said: *"I like Rob's click... It's a nicer noise, so sonically it's nicer to listen to"*. Our participants agreed that the pre-recorded clicking sound from Rob felt more natural.

**6.2.2 Cane sounds.** Participants had different opinions about Cari's pre-recorded cane sounds, with Ken and Cari being more positive. For Ken, the cane sounds felt *"a bit sharper in some ways. I think there was a lot more frequency information in the cane tap than there was in the click"*. Cari said: *"I like the cane, but perhaps that's because it's my go-to [sound], one of them... You're used to [the cane sound] and you know what to do with it and how to use it. It's also that it's so natural that it's comforting, in a way"*. However, Rob said *"I couldn't use them much. And one reason for that, which I hadn't thought about, was that there were several different surfaces in [the recording studio] together. And I used that information of the surface more"*. While Cari and Ken enjoyed the familiarity of the cane sound, Rob would not use it for echolocation, as there would be textural information missing.

## 7 MODELLING TASKS

As described earlier, participants completed a reconstruction task as part of each evaluation session. While the previous sections provided participants' reflections regarding the usefulness of the design decisions implemented for each evaluation session, this section presents the results of participants' modelling tasks. The focus group session made it clear that echolocation in the physical world is used to support acquisition of spatial knowledge; hence our decision to employ a reconstruction task to complement the post-interview. Figure 5 shows the reconstructions of the layouts participants performed on each evaluation session.

As we can observe in Figure 5, all our participants could successfully identify the opening that connected the two areas in the layout they had to explore. However, Cari and Ken could not identify the presence of the obstacle located in the layout of the first evaluation. Regarding the second evaluation session, all participants could locate the presence of the obstacle in the correct position.

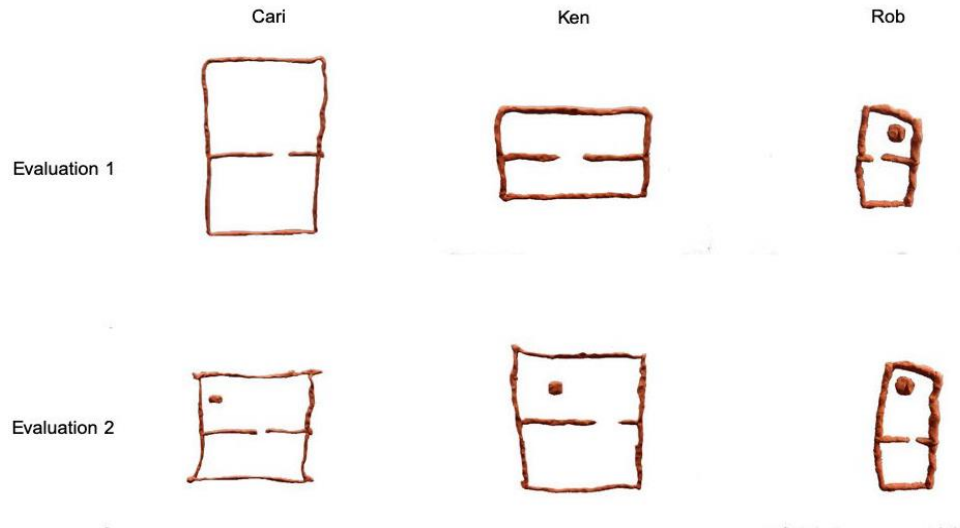


Fig. 5. Clay models produced by each participant after each reconstruction task

This suggests that pre-recorded clicks and the ability to have more precise control over the direction of the virtual avatar may support the development of more accurate mental maps.

Finally, we can observe that for both evaluations not all participants successfully replicated the relative difference in size between the two areas of the different layouts. Although the literature suggests echolocation can be used to detect size of objects [46, 76], it may be more difficult to apply this skill to detect relative size of rooms.

## 8 DISCUSSION

This paper describes a participatory design exercise that led to the elicitation of seven design recommendations, and subsequent implementation of four design decisions. These recommendations were identified by a group of expert echolocators and aimed to improve an existing implementation of echolocation in virtual worlds. We learnt that ambient sounds provide opportunities for passive echolocation, mechanisms to place auditory landmarks should make the landmarks easy to find, providing orientation cues supports the construction of a mental map of virtual space, and using pre-recorded sounds from expert echolocators produces a more pleasant auditory experience that, according to participants, provides them with more information due to its shortness and sharpness. This discussion will focus on the implications of using a participatory design approach in the design of virtual worlds that are more inclusive to people with visual impairment, the relationship between auditory landmarks, compass point information and spatial orientation in virtual worlds, and the effect of using pre-recorded familiar sounds on the overall experience.

### 8.1 Participatory design and the design of technologies for people with disabilities

Disability is a complex issue where the diagnosed medical condition, the subjective lived experience, and the societal context converge [69]. Previous approaches to understanding disability have overlooked some of these aspects and followed a deficit-driven approach. This has led to the development of technologies that aim to "normalise" the situation of the person with disabilities. [47, 61, 89]. Moreover, it might be tempting for technology researchers and designers to rely on

this deficit-driven approach, as it provides a list of functional requirements based on the perceived limitations of individuals [24]. However, we argue that the design of technologies for people with disabilities must recognise the unique skills they have developed through their lived experience. This is critical for technologies such as VR and AR, as they approach near-maturity [90], especially as previous evidence suggests that not considering the opinions of people with disabilities in the design of technologies targeted to them leads to the abandonment of such technologies [55]. Participatory design, with its strong emphasis on learning from users, provides an approach that allows us to move away from a discourse of normalisation and towards a discourse of empowerment [48, 61], where design solutions are truly built upon the lived experience of people with disabilities.

Participatory design is historically rooted in a Marxist/Socialist commitment to empowering workers and fostering ownership in the workplace [11, 81]. When adopted by researchers, this translated in an active engagement with users in design, low-fidelity prototyping, and a strong focus on learning from users. However, it has been argued that participatory design has forgotten its historical roots, and seems to focus on more local issues of usability and user satisfaction instead of addressing issues of power and agency, as it was originally intended [9, 10]. This paper speaks to the original goals of participatory design by working closely with participants, learning from their lived experiences, prioritising the design decisions they deemed more useful, and quickly prototyping and evaluating these design decisions with them.

Another way in which our participatory design approach recognises the unique skills of people with visual impairments is by avoiding the use of blindfolded sighted participants. Although recruiting blindfolded individuals may seem like a viable practice when it is hard to access participants with a visual impairment, we agree with Silverman's argument that blindfolding individuals may "mislead people about blindness, because it highlights the initial trauma of *becoming* blind rather than the realities of *being* blind" [71]. It is particularly important to recruit individuals with visual impairment when conducting echolocation-related experiments, as sighted people usually don't pay much attention to the acoustical cues of their surroundings in their everyday life [50], and comparisons between blind individuals and blindfolded sighted counterparts performing echolocation tasks have shown that people with visual impairment perform better than sighted individuals [38, 64].

Previous research with gamers with visual impairment has found that these gamers feel like games available to them are overly simplistic and do not offer great replayability value [3, 83]. Moreover, people with visual impairment have indicated that game development technologies are not accessible [4]. Hence, learning about the lived experiences of people with visual impairments through participatory design approaches support the design of tools and experiences that are less likely to be quickly abandoned [55].

## 8.2 Affordances and control

Andrade et al. [4] concluded that providing proper internal control of digital games was key for people with visual impairment to have access to them. Our participants have described how important it is for them to have control over the soundscape of the virtual world. They have explained how reducing the volume of ambient sounds helped them receive more echolocation signals, and how in the physical world external sounds such as that of strong wind or rain affect their echolocating skills. Similarly, in previous research, expert gamers with visual impairment have described how desirable it is to have control over the different sounds occurring during, for example, action scenes in games [4]. Virtual experiences in general, and those aiming to implement echolocation in particular, should give players the ability to control the volume of the different sound elements in the in-game experience instead of providing a single master volume control [82].



Playing games is an embodied activity [33, 34]. Moreover, a game controller acts at an operational level as a tangible intermediary between the gamer and the affordances provided in-game [20]. Previous research has explored the use of mainstream videogame controllers when designing experiences for people with visual impairment [17, 75, 86]. However, the most common practice in existing games for people with visual impairment is to use a standard keyboard for user input [65]. The fact that participants did not have any trouble with the Xbox controller even though the mapping of the commands available to them changed after each evaluation highlights the importance of providing a controller that is usable and as Cari described, provides a "mnemonic" for certain affordances. Given the lack of standard earcons to indicate common actions in audiogames [3, 25, 82], including support for mainstream game controllers may better support people with visual impairment experiencing digital games.

### 8.3 Landmarks and passive echolocation to support exploration

Landmarks are defined as fixed points in space in the context of orientation and mobility training [16, 22]. Landmarks are an important tool for the construction of a mental map of one's surroundings, particularly for people with visual impairment, as these allow people with visual impairment to subdivide space into smaller, more manageable pieces [16, 70]. Research on echolocation in the physical world has used stationary objects as landmarks [32, 46, 73], and in virtual worlds Neidhardt et al. [50] and Pelegrin et al. [54] proposed the use of active echolocation for the identification of a wall. However, very little is known about passive echolocation both in the physical and in virtual worlds. In this research, a dialogue with expert echolocators informed the design of a virtual world that supports the inclusion of auditory landmarks and provides an opportunity for passive echolocation.

Regarding the inclusion of auditory landmarks, participants described the importance of ambient sounds, such as ventilation fans, in the physical world, as these sounds provide fixed reference points. We found that these sounds helped participants orient themselves in the virtual space. Moreover, we found that the ventilation fans provided an opportunity for passive echolocation; as Cari described, she could hear the "whoosh" sound of the ventilation fans through the opening. Furthermore previous research concluded that it was hard to identify openings through active echolocation in virtual worlds [FORTHCOMING]. In contrast, the use of passive echolocation provided the following advantages to participants: it gave them a fixed point of reference to orient themselves in a virtual space, and it facilitated finding openings by relying on the reflections of the sounds generated by the sound sources.

### 8.4 Orientation cues and the construction of mental maps of virtual space

Previous research had identified that people with visual impairment require constant orientation cues to successfully build a mental map of a space [21, 22]. The focus group session conducted in this study highlighted the role of echolocation as a means to obtain constant orientation cues, and during our second evaluation session, all participants had positive comments regarding the ability to control the direction they were looking with specific buttons in the Xbox controller. The mapping between the buttons and the compass points—in the words of our participants—felt natural, provided a mnemonic guide, and allowed our participants to form an "absolute map" of the virtual space. Our approach to providing orientation cues strikes a balance between usefulness, freedom for exploration, and delivering an experience that is not overly simplistic [3].

Our participants enjoyed the ability to explore a virtual world where they were not limited to four directions of movement. In contrast, several popular audiogames, such as *Swamp* [6] and *Survive the Wild*, divide virtual space in a grid-like system [26]. According to our participants, a grid-like navigation approach could be detrimental to their ability to form a mental map. This shows that

people with visual impairment wish to experience games that are as complex as those available to sighted players [3, 72] and that providing good representations of space is key to making games more accessible [4].

### 8.5 Richness of pre-recorded sounds

To the best of our knowledge, this is the first study where the clicking sound of an expert echolocator was recorded and then used as a means for active echolocation in a virtual space. Previous research had produced an artificial clicking sound based on a mathematical model derived from samples from expert echolocators [80], and others had let non-experts produce their own clicking sounds to echolocate [54]. Based on our participants' experience, the use of a pre-recorded echolocating click is subjectively better than using artificial clicking sounds, and participants attributed this to the sound feeling "more natural". Although it is hard to generalise, letting expert echolocators record and use their own clicking sounds may improve the gaming experience of people with visual impairment, especially as the use of echolocation enhances the sense of ownership over a virtual experience [5]; however, considerations about the quality of the recording must be made. Future research could explore whether it is necessary to record the clicking sound in an acoustically treated environment, as we did, or if an at-home recording may provide the same subjective advantages over an artificial click.

### 8.6 Future work

While this paper presents valuable findings regarding the implementation of echolocation in virtual worlds, there are several avenues open for future research. For example, participants emphasised the importance of "sound textures" and their potential as landmarks. Modern videogames take great care in the quality of the different sounds, with the sound experience being key to immersion [31]. Future research could explore the effectiveness of a rich sound textures library in assisting people with visual impairment on the creation of a mental image of virtual space. Moreover, future research could investigate how different clicking sounds interact with these sound textures. Similarly, future research could use other pre-recorded commonly used sounds for active and passive echolocation, such as finger snaps, claps, or vehicle sounds, and analyse whether there are differences in subjective usefulness of these different sounds.

Although we provided support of the directionality of the echolocating click with our mapping of the compass points into the buttons of the Xbox controller during the second evaluation stage, participants described a different type of directionality, where the clicking sound is more constrained and described as an "acoustic gun". Future research on echolocation in virtual worlds could explore whether such approach improves the ability of people with visual impairment to form a mental image of virtual space.

## 9 CONCLUSIONS

People with visual impairment have expressed fear of being "left in the dust" by new and emerging technologies such as virtual and augmented reality [3]. Given the current state of near-maturity of such technologies [49], there is an opportunity for the design of solutions that will enable people with visual impairment to access these experiences. It is crucial to recognise the unique skills that people with visual impairment have developed through their lived experience of disability in the design of these accessibility solutions, so as to avoid the implementation of solutions that take a deficit-driven approach [47, 61]. Given its focus on learning from users, participatory design methods may provide rich and unique insights that lean on the lived experience of people with disabilities to inform the design of accessibility solutions.

Through our participatory design study, we aimed to improve an existing implementation of echolocation in virtual worlds by learning from a group of expert echolocators. The experts provided a series of design recommendations based on their lived experience as echolocators, and their previous experience using an echolocation-enabled virtual world. Participants highlighted: the importance of passive echolocation, the role of auditory landmarks in the process of building a mental map of virtual space, the more pleasant experience provided by pre-recorded clicking sounds over sounds that were artificially produced, and the importance of providing a means to control the direction of the virtual in-game character. Participants also discussed the importance of providing different "sound textures" and the role of external factors such as the weather when using echolocation. Our prototype evaluations teased the usefulness of some of these ideas in the formation of a mental image of virtual space.

Echolocation is becoming a more popular tool to make virtual worlds more accessible for people with visual impairment, as demonstrated by the recent research conducted in this area [2, 5, 54, 88]. With our work, we support further development of echolocation-based virtual worlds by providing a series of design recommendations elicited from expert echolocators. Such recommendations may inform further development of echolocation-enabled virtual worlds and may encourage the development of echolocation as a novel interaction technique that is based on the strengths developed by people with visual impairment through their lived experience of disability.

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### **A APPENDIX: QUESTIONS THAT GUIDED THE FOCUS GROUP AND POST EVALUATION INTERVIEWS**

#### **A.1 Questions that guided the focus group session**

- What is your preferred method of echolocation (tongue clicks, clapping, stomping) and why?
- You all use environmental sounds to negotiate your surroundings. Could you go into more detail? How are these sounds different in the sense of the information that they give?
- Do you have any experience with binaural recordings?
- What would be the best way to describe the effect of using echolocation?
- What would be, for you, the perfect echolocating sound?
- How did the echolocation-enabled virtual world you've been exposed to compare to the lived experience you have as echolocators?
- How did everyone feel about the directional cues provided in the echolocation-enabled virtual world you've been exposed to? How would you improve them?
- How does the presence of objects in a physical room affect your echolocation?
- We have been talking mostly about in-door spaces. How does echolocation change in out-door spaces?
- If you were able to enhance your echolocation through a device or something that you would carry it with you, what would that something look like?
- How or when did you first realize you were echolocating?
- How did you learn to echolocate?
- Walk me through a normal day in your life and tell me what role echolocation plays in it.
- What's the image that you get in your mind when you use echolocation?
- What elements can hinder your ability to echolocate?

#### **A.2 Questions that guided the post interview after the first evaluation session**

- Please describe the layout you have recreated. Was it the same layout in both trials?
- What information did the use of the ventilation sounds convey?
- How did the use of ventilation sounds improved or worsened the experience when compared to the previous sterile environment you had been exposed to in the past?
- How did changing the volume of the fans affect the experience?
- What was your opinion about the coins?
- How else would you convey landmarks?
- How did the use of coins improve or worsened the experience when compared with the previous sterile environment you had been exposed to in the past?

#### **A.3 Questions that guided the post interview after the second evaluation session**

- Please describe the layout you have recreated. Was it the same layout in both trials?
- What was the impact of having control over the direction in which the character moved?
- With the addition of the control in direction came a change in the layout of the controls in the Xbox controller. What are your thoughts about that?
- How were the recorded clicks different from the artificial clicks?
- What was your opinion about the cane sounds?
- How do the cane sounds compare to the clicking sounds?
- What are your final thoughts on the four options we have tried: ambient noises, the coins as landmarks, fixed compass points and recorded clicking sounds?



## 8.5. Discussion

This chapter makes a number of contributions to this thesis. One of them is the direct inclusion of the voices of participants with lived experience both with visual impairment and as expert echolocators in the design process. This was facilitated via a participatory design approach that focused on co-learning with participants in order to improve upon an existing design (Robertson et al., 2014). Although there have been previous implementations of echolocation in virtual worlds (Pelegrin Garcia et al., 2014; Picinali et al., 2014; Rowan et al., 2013; Schörnich et al., 2012; Wu et al., 2017), these have not been informed by the lived experiences of expert echolocators. Moreover, the participatory approach presented in this chapter is in line with the critical realist view that informs this work, as it helps to build a multi-faceted and interactional understanding of disability and technology by learning from the lived experiences of people with visual impairment, while at the same time placing emphasis in the need of empirical evidence, obtained through experimentation (Frauenberger, 2015; Shakespeare, 2013).

Other contributions made in this chapter are the elicitation of the following seven design recommendations developed by participants:

1. Use sounds that are sharp, short and familiar
2. Provide opportunities for passive echolocation
3. Do not expect echolocation in virtual worlds to be the same as echolocation in the physical world
4. Support directionality of the echolocating sound
5. Provide sounds with different “textures”
6. Facilitate inclusion of landmarks
7. Consider how external factors affect echolocation

The literature outlines a distinction between active echolocation—where users produce distinct sounds such as clicking tones with their tongues to echolocate—and passive echolocation—where users listen to the echoes produced by sounds that occur naturally in their surroundings (Ashmead et al., 1998; Stroffregen & Pittenger, 1995). However, no experiments with human echolocators have explored the usefulness of passive echolocation before—though passive echolocation has been explored in dolphins (Xitco & Roitblat, 1996) and bats (Russo et al., 2007). Hence the decision to provide passive echolocation capabilities in the first evaluation cycle (design guideline 2) was made. The first evaluation cycle also included the ability to place auditory landmarks in virtual space (design guideline 6). This was done because the need for orientation cues has been a constant finding, identified in studies 2A and 2B, presented in both chapters six and seven.

The second evaluation cycle saw the implementation of key bindings to control the virtual character's direction as a response to design guideline 4, and the use of participants' pre-recorded clicking sounds to support design guideline 1. The implementation of these design guidelines improved participants' ability to detect openings and obstacles in a virtual world. As study 2B had identified that obstacles and openings were difficult for participants to detect, the findings presented in this study demonstrate the importance of involving people with disabilities in the design of technologies targeted to them.

Finally, the remaining three design recommendations are of particular importance for the development of enticing virtual experiences for people with visual impairment. These are: design guideline 3: do not expect echolocation in virtual worlds to be the same as echolocation in the physical world, guideline 5: provide sounds with different

“textures” and guideline 7: consider how external factors affect echolocation. These guidelines ask us to consider the richness of the physical world for inspiration, but to not get fixated on replicating it. This is in line with Norman (2008), who argues that overly literal metaphors may make it difficult for users to recognise the potential for action provided by the metaphor.

Overall, section III has described how to implement echolocation-enabled virtual worlds targeted at supporting people with visual impairment to acquire spatial knowledge. The implementation of echolocation presented in this thesis has proceeded from feasibility to in-depth analysis to refinement. Unlike previous implementations of echolocation in virtual worlds, feedback from people with visual impairment has been critical for the development of each stage of the implementation. More specifically, this chapter has presented a series of design guidelines aimed at the development of richer virtual experiences for people with visual impairment. Just like in chapter four and five, this chapter places the voices of people with disabilities front and centre, concluding a series of laboratory-based evaluations seeking to implement echolocation in virtual worlds. The next—and last—chapter of this thesis will look at how the knowledge gained in Section II about gamers with visual impairment and the implementations of echolocation presented in Section III contribute to different fields of knowledge.



# Chapter 9: Discussion and Conclusions

## 9.1. Introduction

In this thesis, I have explored the research question: *how can echolocation be designed as a means for people with visual impairment to acquire spatial knowledge of virtual space?* To answer this question, I employed a pragmatist approach. This approach has been realised through a critical realist lens that promotes a holistic understanding of disability where both the lived experience and external factors are taken into consideration (Shakespeare, 2013). To address the main research question posed above, I devised a series of user studies that addressed different aspects of the question, presented through five sub-research questions, listed in chapter one, and explored across chapters four to eight.

This chapter presents an integrated discussion of all the studies. This discussion starts with a summary of the key findings from each of the studies conducted as part of this thesis (section 9.2). This is followed by a discussion of how these findings relate to: giving voice to people with visual impairment (section 9.3.1), designing echolocation-enabled virtual environments (section 9.3.2) and how these echolocation-enabled virtual environments support the acquisition of spatial information (section 9.3.3). Additionally,

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this chapter discusses implications of this work for the fields of human-computer interaction (section 9.4.1), game design (section 9.4.2) and orientation and mobility (section 9.4.3). This chapter ends by outlining the strengths and limitations of this research and presents concluding remarks.

### 9.2. Key findings

This section presents a summary of the key findings from each of the studies conducted in this thesis and their relation to each of the sub-research questions presented in chapter one. The table below presents the relationship between each research question, study and the chapter where the study is presented.

Table 1. Research questions and studies conducted in this thesis.

| Research question                                                                                                     | Study    | Chapter        |
|-----------------------------------------------------------------------------------------------------------------------|----------|----------------|
| RQ1: How do people with visual impairment currently engage with virtual spaces?                                       | Study 1  | Chapters 4 - 5 |
| RQ2: How can echolocation be implemented in virtual worlds so that it supports the acquisition of spatial knowledge?  | Study 2A | Chapter 6      |
| RQ3: What features of virtual space can be revealed through echolocation?                                             | Study 2B | Chapter 7      |
| RQ4: How do the features revealed through echolocation support the acquisition of spatial knowledge in virtual space? | Study 2B | Chapter 7      |

|                                                                                                            |         |           |
|------------------------------------------------------------------------------------------------------------|---------|-----------|
| RQ5: How can a co-creation process inform the design and implementation of echolocation in virtual spaces? | Study 3 | Chapter 8 |
|------------------------------------------------------------------------------------------------------------|---------|-----------|

The following sub-sections provide answers to each one of the sub-research questions by examining the key findings from each user study.

9.2.1. RQ1: How do people with visual impairment currently engage with virtual spaces?

This question was addressed via study 1, which is presented across chapters four and five. Study 1 employed an online survey and in-depth interviews to explore: a) the habits, opinions and concerns of a group of gamers with visual impairment, and b) the elements that, according to this group of gamers, enable access to digital games in the first place. The key findings from study 1 are as follows:

**Finding 1: some gamers with visual impairment desire to engage with digital games that are as rich as those available to sighted players. But there is a tension between accessibility and complexity.**

Study 1 provided unique insights into the habits of gamers with visual impairment. It provided a summary of the types and genres of games people with visual impairment play, the frequency and length of their playing sessions, the devices they use to access digital games, and the assistive technologies they rely on when engaging with these games. While these trends are well documented in the gaming industry (see ESA (2020) for trends in the gaming industry in the US, or Brand et al. (2019) for Australian trends), study 1 was the first to explore these trends among the community of gamers with visual

impairment. Furthermore, study 1 revealed similarities between the relationships of both sighted and visually impaired people with digital games. For example, both groups engage with digital games because of the social component afforded by games; the majority of both sighted and visually impaired gamers engage with digital games for one to two hours; and both groups engage with games for entertainment purposes.

Despite these similarities, the gamers with visual impairment who participated in study 1 also described how, in their opinion, the games that are available to them—mainly audiogames and text-based adventures—are overly simplistic. Furthermore, they argued that the simplistic nature of audiogames renders them unattractive to sighted players. According to Urbanek and Güldenpfennig (2019), this un-attractiveness means that audiogames cannot gain traction and become part of the mainstream gaming scene. This creates a feedback loop where the perceived un-attractiveness of audiogames prevents more people to engage with them. This then leads to less interest in developing more attractive audiogames.

Additional to audiogames being perceived as simplistic, gamers with visual impairment perceive new and emerging technologies, such as virtual and augmented reality (AR/VR), as something that would leave blind players “in the dust” as these experiences are not accessible. Moreover, it could be argued that current approaches to game design have already left visually-impaired gamers behind: several gamers with low vision have described how the introduction of 3D graphics in the mid-90s meant that they were no longer able to engage with mainstream digital games, as graphics suddenly became more complex—as identified in chapter four and in work by Urbanek and Güldenpfennig (2019). It is necessary to make AR/VR experiences accessible by design so that gamers with visual impairment are not left behind once again (Mott et al., 2019).



**Finding 2: Relationships with information and with elements of control are crucial for the development of games that are accessible to people with visual impairment.**

Chapter five introduced the Gamer-Information Control (GIC) framework. This framework highlighted the importance of the relationships between in-game information, gamers and both internal and external elements of control. Moreover, the framework explained that these relationships occur both when gamers engage with digital games as both players and creators. Regarding how information is conveyed, the framework emphasized the importance of conveying spatial information through adequate metaphors and described how existing games use metaphors inspired by real-world phenomena to convey information. While there has been research providing recommendations on how to design more accessible digital games for people with visual impairment, (Atkinson et al., 2006; Trewin et al., 2008; Urbanek et al., 2018), the GIC framework was the first to elicit these recommendations from the perspective of gamers with visual impairment. This approach to creating the GIC framework supports the critical realist nature of this thesis, as it emphasizes the value of the lived experience of people with visual impairment (Shakespeare, 2013).

**Finding 3: conveying spatial information is critical to accessibility in digital games for people with visual impairment.**

The GIC framework highlighted the importance of conveying spatial information to design accessible games. Participants explained that so-called 3D games for blind people enabled them to move in four directions (up, down, left, right) and described how certain metaphors, such as echoes, are used inconsistently across games to convey spatial features. For example, participants said, in one game echoes may be used to indicate the presence of a wall, but in other they could be used to indicate the presence of a precipice.

Although the lack of consistent metaphors in audiogames is known to be a problem (White et al., 2008), the inconsistent use of echoes presents an opportunity to leverage their use and establish a cohesive and coherent metaphor.

9.2.2. RQ2: How can echolocation be implemented in virtual worlds so that it supports the acquisition of spatial knowledge?

Armed with the knowledge that spatial information is fundamental to accessibility of digital games and that echolocation is employed in the physical world to obtain spatial information of one's surroundings, study 2 sought to explore echolocation in virtual worlds in depth. This study, presented across chapters six and seven, was divided into two parts. The first part—labelled study 2A—consisted of a proof-of-concept laboratory-based evaluation of an implementation of echolocation in a virtual world. Key findings from study 2A were the following:

**Finding 1: it is possible to create an implementation of echolocation using off-the-shelf software, enabling participants to detect the presence of certain elements of virtual space.**

The implementation of echolocation developed in study 2A was created using the game development program *Unity* version 2018.3 and the *SteamAudio* plug-in version 2 beta 10. The same tools were used in subsequent user studies so as not to introduce variability due to changes in the software. The *SteamAudio* plug-in is responsible for simulating how sound is reflected and absorbed by different materials, handling sound occlusion and providing a generic head-related transfer function (HRTF) to simulate differences in milliseconds on how sounds reach a person's left and right ears. With the implementation

of echolocation presented in study 2A, participants could detect the presence of walls and virtual drawers. Being able to detect these features suggested the potential of echolocation to convey more detailed spatial information. This demanded further exploration. Although other implementations of echolocation in virtual worlds, such as those presented by Andreasen et al. (2018) or Wu et al. (2017), have used the same off-the-shelf components, the implementation presented in study 2A was the first created with the goal to assess if the use of these components would support acquisition of spatial information.

**Finding 2: for successful use of echolocation in virtual worlds, users need to be provided with proper scaffolding.**

Scaffolding is a well-known strategy in the context of education and refers to assisting the development of new skills by providing learning aids (Belland, 2014). Participants in study 2A explained that it took them some time to learn to interpret the echo signals provided by the environment and that spending more time in the virtual environment or exploring a training level first would have improved their performance. Participants also identified a need to provide additional orientation cues. They argued that there was not enough information about the direction they were facing, which made it easy for them to lose track of their position in the environment. This is consistent with previous research that established that people with visual impairment need constant orientation cues to navigate virtual environments (Darken & Peterson, 2001; Wu et al., 2017).

These findings informed the design of virtual worlds used in subsequent user studies. Study 2B incorporated a training level and study 3 provided participants with precise control over the direction their virtual avatar faced. Integrating participants'

feedback into design reflects the critical realist nature of this work, as discovering what works for people with disabilities is informed by their opinions (Frauenberger, 2015).

**Finding 3: implementing echolocation in a virtual environment needs compromise: physical echolocation has properties that need more exploration before they are successfully replicated.**

Two expert echolocators participated in study 2A. They spoke at length about the differences between echolocation in the physical and in the virtual world. Particularly, participants described how the echolocating sound provided was less sharp than the sound they would use in the physical world. Participants also explained that they considered the delay produced as sound reaches each ear to be “too quick” when compared with the delay in the physical world. This could be attributed to the use of generic HRTFs, as HRTFs depend on the anatomical shape of the ears and torso of each individual (Poirier-Quinot & Katz, 2018). Despite the influence of generic HRTFs, findings from studies 2B and 3 and previous research by Berger et al. (2018) indicate that the use of generic HRTFs is sufficient to complete tasks that involve the use of sound in virtual worlds. Moreover, participants’ ability to complete the task presented in this study—and in following studies—provides evidence of the usefulness of generic HRTFs.

### 9.2.3. RQ3: What features of virtual space can be revealed through echolocation?

Knowing that echolocation can be implemented in virtual worlds to support acquisition of spatial knowledge, the next step of this research aimed to discover the specific features of virtual space that can be detected with echolocation. This was explored in the first part of study 2B—itsself subdivided in two parts—by designing a laboratory-based evaluation

that included the use of quantitative mixed-effects logistic regression models and qualitative interviews. These are the key findings from study 2B, part 1:

**Finding 1: participants are capable of identifying: (i) the material that a virtual room was made of, (ii) the relative size across three different virtual rooms, and (iii) the presence of 90-degree turns to the left or right approximately 70% of the time.**

Studies in the physical world have explored how people with visual impairment used echolocation to detect the material certain objects were made of (DeLong et al., 2007), the relative size of objects (Teng & Whitney, 2011), and the presence of obstacles (Rosenblum et al., 2000; Supa et al., 1944). Moreover, echolocation in virtual worlds has been used to detect the presence of walls (Pelegrín-García et al., 2018) and obstacles (Andreasen et al., 2018). The findings from study 2B are unique because, unlike previous studies: a) this is the first study to combine several spatial features in a single study, thus providing a wider scope; and b) it is the first study to work with a larger number of people with visual impairment, as previous research has relied on groups of sighted blindfolded individuals whose performance is compared against that of a single blind individual, or it has not included blind individuals at all. As described in chapter three, the only way to identify what works for people with visual impairment is to work with them directly (Frauenberger, 2015). Working exclusively with people with visual impairment lends more validity to the findings from this and the other studies presented in this thesis.

People with visual impairment construct a mental image of their surroundings by establishing the location of specific landmarks in space (Kitchin & Jacobson, 1997). Finding that people with visual impairment could successfully use echolocation to identify materials, sizes and turns is an important first step in assisting them with the formation of a mental map of virtual space. People with visual impairment have expressed

previously—in study 1 and in research by Urbanek and Gldenpfennig (2019)—that one of the reasons they engage with digital games is to explore new worlds. Knowing that echolocation facilitates the identification of specific landmark features is an exciting first step towards more accessible games where people with visual impairment are able to explore the game world in equality of conditions as any other player.

**Finding 2: there is no significant evidence that participants can successfully identify the presence of openings and obstacles.**

Although previous research has found that people with visual impairment can identify the presence of walls in the physical world (Supa et al., 1944) and that sighted blindfolded individuals can learn to identify walls in virtual worlds (Pelegrn-Garca et al., 2018), not much is known regarding the ability of people with visual impairment to identify walls and other obstacles in virtual worlds. Moreover, it is not clear why it was hard for participants in study 2B to identify openings and obstacles. While participants agreed that identifying openings and obstacles was harder than identifying materials, relative size of rooms and the presence of turns, they did not articulate why this was the case. This finding demonstrates the need to further investigate echolocation and how it can be used to learn about specific features of virtual space.

9.2.4. RQ4: How do the features revealed through echolocation support the acquisition of spatial knowledge in virtual space?

The second part of study 2B consisted of a reconstruction task where participants used modelling clay to recreate a virtual space they explored. This was followed by interviews. These are the key findings from study 2B part 2:

**Finding 3: nine out of twelve participants could successfully integrate several landmark features and create very accurate models.**

When presented with a virtual layout comprised of two rooms of different sizes connected by an L-shaped corridor, nine out of twelve participants were able to produce a reasonably accurate replica of the layout. In order for participants to create a mental map of virtual space, they relied on a perimeter exploration technique. This technique consists of walking around the walls of an environment without bumping into them (Lahav et al., 2012). Moreover, participants described how the echolocation capabilities implemented in the virtual world prevented them from bumping into the walls. Participants stated that using perimeter exploration is how they would form a mental map of a space in the physical world. This is an example of how people with visual impairment bring their unique skillset developed through their lived experience when facing new situations (Shakespeare, 2013).

By employing echolocation in a virtual world, participants were able to perceive their surroundings, as evidenced by their ability to recreate them. Since perception is key for transforming a mental map into actual navigation on a given space (Darken & Peterson, 2001; Jul & Furnas, 1997), this finding is crucial, as it demonstrates that echolocation provides an alternative to visual perception to support the ability of people with visual impairment to navigate virtual worlds.

**Finding 4: echolocation helps create a sense of presence in virtual worlds.**

Participants talked at length about how using echolocation in a virtual world enabled them to perceive “the place” and how “sound and space varied”. According to participants, the virtual layouts “by the end were feeling kind of real”. Participants described how the

virtual environment supported their sense of presence. Presence is the feeling of being transported into a virtual world (Sanchez-Vives & Slater, 2005). Seminal research in the field of presence and virtual worlds has established that “presence correlates highly with the degree of association with the virtual body” (Usuh et al., 1999, p. 362). As people with visual impairment cannot see their virtual body, knowing that using echolocation improve the sense of presence is a significant finding. Moreover, this finding matches previous research arguing that the use of spatialised sound cues improved participants’ sense of presence (Hendrix & Barfield, 1996).

**Finding 5: people with visual impairment desire to engage with virtual worlds for entertainment or to improve orientation and mobility skills, even if they have no previous experience with such worlds.**

Only one of the twelve participants involved in study 2B had previous experience playing digital games before losing their sight. However, several other participants mentioned that, if virtual worlds were accessible, they would engage with such worlds either for relaxation purposes or to improve their orientation and mobility skills. This finding supports the idea that play is an inherent aspect of human nature (Huizinga, 2014) and encourages further research in the field of accessibility and game design.

9.2.5. RQ5: How can a co-creation process inform the design and implementation of echolocation in virtual spaces?

Although the implementation of echolocation developed for study 2B proved useful for detecting virtual materials, relative size of rooms and presence of 90-degree turns, to ensure echolocation is useful to explore virtual environments it was necessary to further



explore how to improve detection of openings and obstacles. To ensure that the opinions of people with visual impairment were included during the design stages, study 3 (presented in chapter eight) followed a participatory design approach. These are the key findings from study 3.

### **Finding 1: design recommendations**

From the participatory design exercise presented in study 3, the first key finding is a series of seven design recommendations on how to implement echolocation in virtual worlds. These recommendations, developed by a group of expert echolocators, are:

1. Use sounds that are sharp, short and familiar
2. Provide opportunities for passive echolocation
3. Do not expect echolocation in virtual worlds to be the same as echolocation in the physical world
4. Support directionality of the echolocating sound
5. Provide sounds with different “textures”
6. Facilitate inclusion of landmarks
7. Consider how external factors affect echolocation

The development of these design recommendations is an attempt to provide agency to people with visual impairment during the design stage of echolocation-enabled virtual environments by ensuring their voices are heard and inform future design (Bannon et al., 2018). However, it must be acknowledged that all these recommendations need to be further tested. In study 3 and together with participants, it was decided that four of these recommendations will be implemented. Their implementation led to other findings.

### **Finding 2: passive echolocation is important to build a mental map of virtual space.**

## Chapter 9: Discussion and Conclusions

Participants explained at length how passive echolocation helps them learn about their surroundings without having to actively produce a sound. Participants described how passive echolocation allowed them to “see how a room sounds”, and how this ability was useful when outdoors. Study 3 is the first to describe the significance of passive echolocation for expert echolocators, as no research has explored passive echolocation in humans before, neither in physical nor in virtual environments. However, it must be noted that previous research has explored passive echolocation in other mammals (Russo et al., 2007; Xitco & Roitblat, 1996).

Additionally, participants argued that passive echolocation facilitated the detection of openings. When the virtual environment provided the sound of ventilation fans to be used for passive echolocation, one of the participants explained she could hear the “whoosh” noise of the fans being reflected through the opening. Study 2B previously found that openings were difficult to detect using active echolocation. This new finding, however, indicates that passive echolocation may help detect openings in a virtual world. More research is needed to determine whether passive echolocation can be used to provide support when detecting other spatial features, such as the ones explored in study 2B (materials, size of rooms, turns and obstacles).

**Finding 3: using high-quality pre-recorded clicking sounds from expert echolocators has a positive impact on the subjective experience of participants.**

Participants responded positively to the ability to use pre-recorded mouth-clicking sounds obtained from an expert echolocator. Participants argued that the pre-recorded sound was shorter and sharper than other sounds that had been available to them previously. Moreover, participants argued that the sharpness and shortness of the pre-recorded sound

enabled them to receive more spatial information and produced an overall better subjective experience.

While previous research on echolocation has allowed non-expert echolocators to use their own clicking sounds (Pelegrín-García et al., 2018), this is the first study where pre-recorded clicking sounds of an expert echolocator have been used to navigate a virtual space. However, it must be noted that these sounds were recorded in an acoustically treated environment. Future research may explore whether recordings obtained in a non-acoustically treated environment provide the same positive response.

### **9.3. Discussion**

The previous sections presented a summary of the key findings from each user study conducted in this thesis and outlined how these findings address each one of the research questions posed in chapter one. The following sections discuss these findings in light of the critical-realist approach of this work. This discussion centres around: the need to work together with people with disabilities to develop technology solutions that are suitable to them, the implications of this work for future implementation of echolocation in virtual worlds, and the implications of using echolocation in virtual worlds to acquire spatial knowledge.

#### **9.3.1. The voice of (non) gamers with visual impairment**

Rogers and Marsden (2013) argue that oftentimes the voices of people with impairments are disregarded. Rogers and Marsden (2013) cite the example of the question “does he take sugar?” posed when a person with a disability is offered a hot drink: instead of asking

the person with a disability directly, the question is presented to their carer. This framing of questions and underlying attitudes behind it have been analysed by others (Hogg & Wilson, 2004; Wagner, 1991). More broadly, Scully (2018) and McConkey (2004) argue that such ways of addressing people with disabilities constitute an epistemic injustice, as they exclude people with disabilities from contributing to knowledge or give low credibility or importance to their opinions.

A way to address this epistemic injustice in HCI, according to Rogers and Marsden (2013), is designing for empowerment: effectively becoming a more empathetic research community that co-creates technology with new users in new locations. We may aim to design empowering experiences or empower through the design process (Schneider et al., 2018). Ultimately, designing for empowerment should lead to the experience of being “immersed in interaction” (Moser, 2005). A starting point to achieving this empowerment is learning directly from the experiences of people with disabilities: ensuring their voices and experiences guide design.

Listening to, learning from and ultimately empowering people with visual impairment has been at the core of this work. This way, I have avoided the “does he take sugar?” approach described by Rogers and Marsden (2013). The findings of *RQ1*, which described the habits, opinions and concerns of gamers with visual impairment and the elements that, according to gamers with visual impairment, make games more accessible, reflect this desire to learn directly from people with disabilities. I hope these findings encourage other HCI researchers and game designers to recognise the valuable insights that marginalised groups—such as, in the case of this thesis, people with visual impairment—possess. In recognising the value of the opinions of marginalised groups, this thesis contributes to addressing issues of epistemic injustice (McConkey, 2004).

Apart from addressing issues of epistemic injustice, *RQ1: finding 1* raises awareness about the need to ensure that new and emerging technologies such as AR/VR are accessible by design (Mott et al., 2019). As people with visual impairment have expressed their desire to engage with these technologies in study 1, it is our responsibility as researchers and designers to ensure that these technologies meet their needs. By doing this, we will ensure that gamers with visual impairment are not “left in the dust” by new technological developments. Furthermore, people with visual impairment have provided recommendations on how to make digital experiences more accessible (see *RQ1: finding 2*, *RQ2: finding 2* and *RQ5: finding 1*). Not including the opinions of people with disabilities in the design of technologies targeted to them usually results in abandonment of these technologies (Phillips & Zhao, 1993). It is my hope that the recommendations made by people with visual impairment across the different studies that comprise this thesis be implemented and tested in future research.

Another way this thesis strives to listen to and learn from the voices of people with visual impairment is by involving a wide range of participants from different backgrounds. While study 1 focused on the voices of expert gamers with visual impairment from all over the world, studies 2A, 2B and 3 included participants from Ecuador and Australia, from different cultural and socio-economic backgrounds, whom for the most part, had no experience playing digital games. Although it is not the purpose of this thesis to analyse how people from different backgrounds relate to technology and virtual spaces, it must be recognised that diversity is key to developing notions of learning from others (Morrison & Grbic, 2015). Methodologically, relying on a wide range of participants prevented this work from incurring in selection bias, where a sub-sector of the population is over-represented.

Having a wide variety of participants contributes to more inclusive research and may reveal additional unexpected findings. In the case of this work, for example, *RQ4: finding 5* showed that even participants with no prior gaming experience would engage with digital games for entertainment purposes if these games were accessible. This finding supports the argument that play is embedded in human nature (Huizinga, 2014) and highlights the importance of having worked with both gamers and non-gamers with visual impairment. Future research may strive to include a plurality of participants in their evaluations of accessible technology.

Finally, *RQ4: finding 3* provided an example of how participants brought into the virtual space the skills they had developed through their lived experience, as they relied on a perimeter exploration approach—which consists of walking close to walls—when familiarising themselves with a new (virtual) space (Lahav et al., 2012). Similarly, *RQ5: finding 1* (design recommendations) present another example of the importance of learning from the lived experience of people with disabilities (Shakespeare, 2013), as these recommendations highlighted, among other things, the importance of passive echolocation. Although there is research on passive echolocation in dolphins and bats (Russo et al., 2007; Xitco & Roitblat, 1996), very little is known about the usefulness of passive echolocation for humans. These examples demonstrate the importance of learning from the lived experience of people with disabilities, as both passive echolocation and perimeter exploration are techniques that people with visual impairment use in their day-to-day life. Future research should seek to facilitate the implementation and use of the strategies that people with disabilities have developed as a response to their impairment.

## 9.3.2. Implementation of echolocation in virtual worlds

This research does not present the first attempt at implementing echolocation in virtual worlds. In fact, chapter two presents a detailed review of previous implementations of echolocation in virtual worlds. However, the implementation presented in this thesis is original in that a) it is not limited by trying to replicate echolocation as it occurs in the physical world, and b) it provides an in-depth exploration of usefulness of echolocation to acquire spatial knowledge in virtual worlds.

Implementations of echolocation that have used commercial software to mimic perception of echolocation as accurately as possible have been presented by Schörnich et al. (2012), Pelegrin Garcia et al. (2014), Pelegrín-García et al. (2018) and Picinali et al. (2014). A supposed key element to replicating the listening experience of echolocation stimuli accurately in virtual worlds is creating individual head-related transfer functions (HRTFs) for each user, as these functions are dependent on an individual's physiology and enable the simulation of the differences in milliseconds as sounds reach the left and right ear (Mehra et al., 2016). However, previous research has found that generic HRTFs are “good enough” for use in virtual worlds, especially when multi-sensory stimuli are provided (Berger et al., 2018). Furthermore, *RQ2: finding 3* and *RQ4: finding 3* support the argument that generic HRTFs are sufficient to develop a working implementation of echolocation that can be used to acquire spatial information.

In this research, I implement echolocation in virtual environments using off-the-shelf software that relied on generic HRTFs. According to expert echolocators who participated in studies 2B and 3, this did not prevent them from learning to interpret the feedback provided by the implementation of echolocation they had to interact with. However, participants acknowledged the need for training to learn to interpret the

feedback provided by the virtual environment (*RQ2: finding 2*). According to one of the participants in study 3: “*By the end of [the evaluation] you see a world. It is like learning a code*”. This finding should ultimately dispel the idea that it is necessary to create individual HRTFs to implement echolocation in virtual worlds.

An aspect where we may look at the real world for inspiration is in the creation of sound stimuli that are suitable to use for echolocation in virtual worlds. Throughout studies 2A, 2B and 3, participants could use artificial clicking sounds synthesised from a dataset of clicking sounds obtained from expert echolocators by Thaler et al. (2017). Artificial clicking sounds were chosen because previous research has established that clicking sounds produced with the tongue are the most effective sounds for echolocation in the physical world (Martínez Rojas et al., 2009, 2010). Participants in study 3 could use sounds derived from Thaler et al. (2017) study and pre-recorded mouth clicks obtained from an expert echolocator. When given this choice, participants reported a preference for the pre-recorded sounds (*RQ5: finding 3*). The pre-recorded sounds sounded more natural, according to participants, and conveyed more information. There is still much to explore regarding the usefulness of pre-recorded sounds over artificial clicking sounds. Future research could study whether artificial clicking sounds produced with different parameters of frequency and amplitude would be more effective, or whether pre-recorded sounds could be obtained with a standard microphone in a home setup (the pre-recorded sounds used in study 3 were recorded in an acoustically treated environment).

Finally, current research on echolocation seems to place a strong emphasis on active echolocation, where an individual actively produces sounds and listens to the echo reverberations of these sounds, and a lot less is known about passive echolocation, where



the individual relies on external sounds to obtain spatial cues (Ashmead et al., 1998). *RQ5: finding 2* revealed that passive echolocation plays a crucial role in enabling people with visual impairment to explore their surroundings. Therefore, future research on echolocation in virtual worlds could further explore passive echolocation by introducing different auditory stimuli or by comparing navigation outcomes in settings with and without passive echolocation capabilities.

### 9.3.3. Echolocation as a means for people with visual impairment to explore virtual worlds

As experiences that take place in virtual worlds—such as videogames or VR experiences—become more ubiquitous, it is important to ensure that people with visual impairment are able to successfully explore these worlds so that they can participate in wider cultural conversations, as these technologies permeate our culture. While previous research has sought to provide aids to assist exploration (Trewin et al., 2008), a key contribution of this work is the successful implementation of echolocation to learn about virtual space. Study 2B has demonstrated that the implementation of echolocation presented in this thesis provides an additional tool to assist exploration of virtual space by facilitating detection of virtual materials, size of rooms and 90-degree turns (*RQ3: finding 1*). As echolocation in the physical world is not used in isolation but rather as an additional tool in the toolkit of people with visual impairment (Thaler, 2013), future digital games targeting people with visual impairment may combine implementations of echolocation with other navigation approaches. For example, study 2B identified that obstacles are hard to detect with echolocation (see *RQ3: finding 2*). With this in mind, the “find” tool created by Trewin et al. (2008), which alerts users about the presence of

nearby objects, could be a way to complement echolocation. Having a range of tools available to aid exploration will grant more agency to people engaging with virtual worlds, as they will be able to choose the navigation tool that best suits their needs depending on the circumstances.

The research presented in this thesis is the first to explore how the knowledge of discrete spatial features of virtual space—virtual materials, relative size, left and right turns, openings and obstacles—are combined and assist people with visual impairment in creating a mental map of the space being explored (see *RQ4: finding 3*). The reconstruction tasks used for studies 2B and 3 showed how echolocation in virtual worlds could be used to gain spatial knowledge of virtual space. This finding may be crucial to ensure that people with visual impairment can navigate new types of virtual environments, such as those where the world layout is procedurally generated. In such environments, virtual space is created by an algorithm instead of being a fixed part of the game's assets (Nenad, 2018).

To summarise, the findings from this thesis highlight the desire of people with visual impairment to engage with digital games that are accessible but challenging. This work demonstrates the value of learning from people with disabilities. By doing so, this work seeks to ensure that the voices of people with visual impairment are given equal credibility and importance (McConkey, 2004). Additionally, the findings in this work provide evidence that a generic HRTF is sufficient to develop echolocation-enabled virtual environments. Moreover, findings from this work encourage researchers to observe the physical world for deciding on the best sounds for active echolocation. These findings also shed light on the importance of passive echolocation, a phenomenon that remains unexplored in humans so far. Finally, the findings from this thesis demonstrate

that people with visual impairment can use echolocation to string together a set features and build a mental map of virtual space. As modern games use new strategies to generate game layouts, echolocation may prove useful in making such modern games more accessible.

### **9.4. Implications of this research**

Research does not happen in a vacuum. It builds upon and contributes to an existing body of knowledge in a specific field. This section discusses how this work contributes to the fields of human-computer interaction, game design, and orientation and mobility. For HCI, this thesis argues for the use of echolocation as a novel interaction metaphor to improve accessibility in virtual worlds and advances the idea that critical realism may provide a philosophical anchor to conduct research at the intersection of HCI and disability. For game design, this work recognises the limited existing accessibility options in mainstream games and game development tools and suggests that echolocation could become a new accessibility option that may be implemented in mainstream digital games. Finally, for orientation and mobility, this research highlights the importance of echolocation for developing orientation and mobility skills, while also signalling the usefulness of virtual environments to receive orientation and mobility training.

#### **9.4.1. Human-Computer Interaction**

Harrison et al. (2007) identify three paradigms in the field of HCI. The first paradigm was characterised by human factors and interaction was seen as a form of man-machine coupling. The second paradigm stemmed from cognitive science and strived to

comprehend what happened not only with computing systems, but also with the human mind. Finally, the third paradigm, which Harrison et al. (2007) call *situated perspectives* placed value in context, embodiment and an explicit focus on values in design. I see this thesis as being in-line with the situated perspectives paradigm. To give *context* to this work, study 1 explored the current habits, opinions and concerns of gamers with visual impairment. Salient points from this study included the tension between making digital experiences that are both accessible and enjoyable, and the importance of conveying spatial information to make digital experiences accessible. *Embodiment* is realised at an operational level via the utilisation of a virtual avatar and game controller in studies 2A, 2B and 3 (Conway & Trevillian, 2015). An *emphasis on values* in design is realised through the importance this thesis places on the lived experience of people with visual impairment, as described throughout this work.

Although Harrison et al. (2007) *situated perspectives* in HCI served to “overcome the limitations of prior paradigms to describe socio-technical problems ... the response was mainly methodological” (Frauenberger, 2016, pp. 342-343). The methodological nature associated with this paradigm has raised concerns about the epistemological foundations of HCI (Harrison et al., 2011). This thesis provides evidence that a critical realist lens provides a strong philosophical foundation to HCI inquiry, particularly in the context of HCI and disability. As described in chapter three, the critical realist approach presented in this work recognises the interactional nature of disability, which is comprised of factors both intrinsic and extrinsic to individuals. For HCI research, especially the work within HCI that focuses on improving accessibility, this means that design should go beyond formulating lists of functional requirements in an attempt to “normalise” people with disabilities. Design should instead lead to empowerment and being immersed in

interaction (Frauenberger, 2015; Moser, 2005; Rogers & Marsden, 2013). A critical realist approach can provide a strong foundation for HCI research by encouraging researchers to situate themselves in the context of people with disability and learn from their lived experience.

This thesis has demonstrated the value of echolocation as a novel metaphor to assist people with visual impairment in the acquisition of spatial information in virtual worlds. While this has implications for accessibility research within HCI, its implications are better understood in the context of game design and orientation and mobility. These implications are described below.

### 9.4.2. Game design

Rogerson (2018) describes how gaming is an assemblage between the *gamer*, the *games* and the *gaming* experience. Study 1, particularly as described in chapter four, explored the worldview of the *gamer*, the reasons why gamers engage with digital games, the social trajectories they build around games, and their concerns around new and emerging gaming technologies. Chapter five explored the *games* gamers with visual impairment engage with, and the features that, in the opinion of the gamers, makes these games accessible. Chapters six through eight focused on enriching the *gaming experience* through the implementation of echolocation to enable exploration. The analysis of this work regarding the gamers, the games and the gaming experiences demonstrate thorough consideration of how this work fits in the context of game design. Notably, eleven out of twelve participants who participated in study 2B, described in chapter seven, did not have any previous experience with digital games, but the implementation of echolocation they were presented with made them consider the potential of engaging with digital games as

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a means of relaxation. This demonstrates that a thorough understanding of gamers, games and gaming experiences can produce results that entice non-gamers to engage with games.

In the context of accessibility options in mainstream games, the game with the largest number of accessibility options at the time of writing this thesis is *The Last of Us Part II (PlayStation 4 version)* (2020). Features for people with visual impairment include audio cues for combat and navigation, navigation assistance, among many others. The inclusion of a large set of accessibility features indicates that the gaming industry is starting to realise the importance of such features to reach a wider audience. Moreover, providing navigation assistance signals the importance of navigation in order to engage with digital games.

Echolocation has the potential to become a novel gaming metaphor to support people with visual impairment as they explore digital games. Ultimately, successful implementations of echolocation in digital games may lead to people with visual impairment engaging with these games with the same level of agency and efficiency as their sighted counterparts (Smith & Nayar, 2018) and without attracting undesired attention due to their disability (van de Ven et al., 2005). Echolocation may support people with visual impairment as they engage in gaming experiences that provide an experience that is equitable when compared to that available to sighted players (Smith & Nayar, 2018).

If the implementation of echolocation presented in this thesis was broadly adopted in game design, it could provide a consistent metaphor for use in audiogames. Previous sections indicated that having inconsistent metaphors in audiogames is a known issue (White et al., 2008). Moreover, participants in study 1 explained how current audiogames

make use of echoes to provide sometimes opposing information. For example, participants said, some games may use echoes to indicate the presence of walls while others may use them to indicate the presence of precipices. Providing a unique affordance to the use of echoes in digital games—namely the ability to help detect materials, turns, openings and other spatial features—will reduce cognitive load on gamers, who will have a consistent metaphor across different games.

Additional aspects that this thesis discusses are the accessibility of game development tools and the black-box nature of some of these tools. In chapter five our participants discussed their own role as game creators, lamented the fact that game development tools, such as *Unity*, are not accessible, and argued that if these tools were accessible, they would create their own games. Modding—modifying the code or assets of a game—is a manifestation of participatory culture that enables gamers to mould a game as they see fit (Sihvonen, 2011). Although such capabilities are not currently available to gamers with visual impairment, games that support a discourse of empowerment (Rogers & Marsden, 2013) may need to consider including such capabilities.

### 9.4.3. Orientation and mobility

The use of echolocation in the physical world has been associated with better orientation and mobility outcomes in both familiar and unfamiliar places (Thaler, 2013). This was investigated in Study 3, where conversations with expert echolocators revealed the role echolocation plays in assisting them in the creation of a mental map of their surroundings. Even participants in study 2B who do not use echolocation argued that an echolocation-enabled virtual environment may support them in learning the layout of a physical

location, thus making them feel safer if they first explored a virtual location modelled after a physical site. Successfully developing orientation and mobility skills is a key enabler for people with visual impairment to live a more independent life (Kelley, 1996). Furthermore, research has found that successful formation of mental maps—and subsequent successful development of orientation and mobility skills—relies on the use of multimodal (auditory, olfactory, kinaesthetic) information (Ishmael, 2015). As such, echolocation as a means to support acquisition of spatial knowledge in virtual space may play an important role in improving orientation and mobility outcomes for people with visual impairment, as this knowledge could then be transferred to the physical world.

Initial research by Lahav et al. (2012) suggested the use of virtual environments as training simulators for the development of orientation and mobility skills. Moreover, Connors et al. (2014) have found that blind people who explored a virtual environment that was modelled after a real-world location were more successful in exploring the matching physical location. Although the virtual environments implemented in studies 2A, 2B and 3 in this thesis were not modelled after physical locations, participants saw the potential of echolocation-enabled virtual environments as a training tool to become familiar with unknown physical spaces (see *RQ4: finding 5*). Therefore, more research is needed to identify if echolocation-enabled virtual environments can be used to people with visual impairment to become familiar with physical locations.

In the study presented by Connors et al. (2014), their virtual environment included auditory feedback to indicate the presence of openings and used a grid-like navigation system. On the other hand, studies 2A, 2B and 3 of this thesis implemented an avatar with free directional movement, as opposed to grid-like navigation, and coupled it with orientation cues. As participants in study 3 argued that grid-like navigation systems would



be detrimental to their ability to form a mental map of space, future research may compare the ability of people with visual impairment to build mental maps of virtual space using both a grid-like navigation system and free directional movement. This comparison would help determine best practices to using virtual worlds for orientation and mobility training.

Finally, it is necessary acknowledge that it is important to develop the ability to learn about virtual space for its own sake, not just because this knowledge may be translated back into the physical world. This is especially true for VR experiences. On the one hand, participants from study 1 expressed fears they would be “left in the dust” by the development of VR/AR technologies. On the other hand, Mott et al. (2019) argue that VR/AR technologies are at a stage of “near maturity” and this provides a unique opportunity to ensure these technologies are accessible by design, instead of having accessibility features retro fed into them. Furthermore, Kreimeier et al. (2020) argue that VR “promises expanded access to spatial information” by reducing risk of injury to people with visual impairment. For people with visual impairment to successfully engage with these technologies, it is necessary that mechanisms to facilitate acquisition of spatial knowledge be developed and become a default feature. The implementation of echolocation presented in this thesis may become one such mechanism.

### **9.5. Strengths and limitations**

The analysis of the strengths of this work is inspired by Tracy (2010) article on criteria for excellent qualitative research and the application of these criteria presented by Rogerson (2018, pp. 249-260). The limitations identified in this research are related to access to participants, limitations of existing technology, and time constraints.

### 9.5.1. Strengths

The topic presented in this thesis is *worthy of investigation*. Methodologically, a critical realist lens highlights the importance of interventions that may improve the wellbeing of people with disabilities (Shakespeare, 2013), and games may be such interventions. Furthermore, research has described the tension between creating games that are accessible and enjoyable at the same time (Urbanek & Güldenpfennig, 2019). Previous research has identified that the ability to explore a virtual environment is key to engaging with it (Darken & Peterson, 2001). Therefore, investigating whether echolocation can support people with visual impairment to explore virtual worlds is important to ensure they can access these worlds. HCI is in a privileged position to explore these issues and provide creative solutions due to its pragmatism regarding leveraging knowledge from different fields and using a wide array of research methods (Dourish, 2014).

*Rich rigour* is evident when considering the logical sequence behind each of the user studies conducted in this thesis. Study 1 demonstrates the need for accessible digital games and proposes echolocation as a metaphor to be implemented. Study 2A and Study 2B show how to implement echolocation-enabled virtual environments that support the acquisition of spatial knowledge, and study 3 builds on the findings from study 2B to further explore how to improve the existing implementation of echolocation. Engaging only with people with visual impairment supports the rigour of this work: as described in chapter three, working closely with people with visual impairment is the best way to know what works for them. Finally, the choice of methods on each study support the rigour sought in this work. For example, with the use of mixed methods in studies 1, 2A and 2B and following an explanatory sequential design (Creswell & Plano Clark, 2011), where

qualitative data compliments and offers rich explanations to quantitative findings, the results of these studies provide are complemented.

*Sincerity, credibility* and *resonance* refer to the authenticity of the intent of the researcher, the verisimilitude of the research findings and the potential for the research to resonate with others. As someone with a lived experience of visual impairment and several years' experience teaching people with visual impairment how to use screen-reading software, the intent of this research was always driven by a desire to implement something that would be of benefit to people with visual impairment. Furthermore, working *with* people with disabilities when designing something *for* them adds to the credibility of this work (Mankoff et al., 2010). As I explained in chapter three, the best way to find out what works for people with disabilities is to ask them directly. Finally, this research resonates with the target population. This is demonstrated by the fact that both expert and non-expert echolocators found that they could learn to use echolocation in virtual worlds, and by the fact that people with visual impairment who do not play digital games suggested that they would consider engaging with virtual worlds if these were accessible.

### 9.5.2. Limitations

The work conducted in this thesis was bound by constraints associated with any doctoral program. This section discusses the limitations around access to participants, time constraints and experimental design.

#### **Participant limitations**

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One of the biggest challenges during the development of this work was the recruitment of participants. Given my previous experience working with people with visual impairment, I underestimated how difficult it would be to engage with relevant organisations in a foreign country in order to gain access to participants. Furthermore, it was clear to me that I needed to work with people with visual impairments to ensure the credibility of the results obtained. I tried to engage with organisations that work with people with visual impairment, hoping to reach participants through these organisations, but found that the process was more complicated than I anticipated. As a consequence, study 2A was conducted with a small sample size and study 2B was conducted back in my hometown, where I had a well-established network of contacts of people with visual impairments. A consequence of this relatively small sample size is the potential inability to generalise the results obtained in this thesis. Larger sample sizes are needed to produce results that can be replicated with more robustness in research and practice.

Other limitations surrounding access to participants were related to gender balance and age. Although 55% percent of the population of people with visual impairment identify as female (*Gender and Blindness*, n.d.) and roughly half of all gamers identify as female in countries like the USA and Australia (Brand et al., 2019; 2020), in the studies conducted for this thesis people who identify as female have been underrepresented. In study 1, conducted via online interviews, four out of seventeen participants identified as female. In study 2A, two out of five participants identified as female. In study 2B, two out of twelve participants identified as female, and in study 3, 1 out of 3 participants identified as female. This gender imbalance may be caused by the fact that participants were self-selected and therefore I could not actively control for gender biases.

Regarding participant age, according to the World Health Organisation, “the majority of people with vision impairment are over the age of 50 years” (*Blindness and vision impairment*, 2019). However, in this thesis I have purposefully avoided recruiting participants who have lost their sight due to aging. Although not recruiting people who have developed a visual impairment as a consequence of aging diminished the pool of available participants, doing this was a means to recognise the unique skills that people with visual impairment develop through their lived experience.

The final limitations regarding participants in this research are related to participants’ experience playing digital games and my inability to engage with the same group of participants over time. Although study 1 was conducted with serious gamers with visual impairment, only one participant across studies 2A, 2B and 3 had experience with digital games. Participants with more experience playing digital games might have devised other applications for echolocation in virtual worlds. Similarly, considering that the need to provide adequate scaffolding in order to learn how to use echolocation in virtual worlds was established early in this research, the ability to engage with the same participants across different studies would have enabled me to establish whether there were learning effects.

### **Experimental design limitations**

The main objective of this thesis was to understand how echolocation in virtual environments may support acquisition of spatial knowledge. Studies 2A and 2B presented experiments exploring different aspects of spatial information acquisition in virtual worlds. Despite the positive findings of these experiments, they are not without their

limitations. Particularly, study 2B would have benefitted from a stricter control group where participants would explore a virtual environment that was not echolocation-enabled before exploring the echolocation-enabled environments. However, it is important to remember that echolocation is not used in isolation, but rather as an additional tool for people with visual impairment to explore their surroundings (Thaler et al., 2011). This was also reflected in participants' comments during study 3. When designing the experiments presented in this thesis, it was necessary to balance how echolocation is really used with a limited access to participants.

Another limitation regarding the experimental design is related to the technology employed to create the echolocation-enabled virtual environments used throughout this thesis. Specifically, the black-box nature of the tools used—particularly of the *SteamAudio* plug-in—meant that I did not have control over how sound reverberations, occlusion and material absorption were modelled. Although I had to rely on the parameters provided by the developers of *SteamAudio*, focusing on developing my own sound engine would have reduced my ability to focus on the research question at hand. Furthermore, findings from the studies presented in this thesis demonstrate that *SteamAudio* can be successfully used to develop a functional implementation of echolocation.

### **9.6. Conclusion**

This thesis investigates how echolocation can be implemented in virtual worlds to support acquisition of spatial knowledge by people with visual impairment. This research is informed by a pragmatist approach and a critical realist lens that recognises the importance of both external empirical evidence and the lived experience of people with

disabilities when designing technology interventions. Through this lens, a series of studies were devised.

The first study (Chapters four and five) identified unique insights into the habits, opinions and concerns of gamers with visual impairment, and described the elements that, in the opinion of expert gamers with visual impairment, enabled access to digital games. This study found that people with visual impairment find games available to them to be simplistic, they feared that new and emerging technologies may prevent them from engaging with digital games further, and highlighted the importance of conveying spatial information to enable access to digital games.

Building on these findings, this thesis proposed the use of echolocation to convey spatial information in virtual worlds. Study 2A (Chapter six) found that it is possible to implement echolocation in virtual worlds using off-the shelf components and that this implementation enables the detection of certain features such as virtual walls or drawers. However, this study also identified the need to provide proper scaffolding and easy-to-understand controls to make echolocation usable in virtual worlds.

Once it was established that echolocation could be implemented with off-the-shelf components, study 2B (Chapter seven) provided insights into how echolocation can be used to acquire spatial knowledge of virtual space. Study 2B revealed that people with visual impairment can identify different virtual materials, rooms of different size, and presence of 90-degree turns approximately 70% of the time; and that these features can be integrated to create a mental map of virtual space. However, study 2B also identified that people with visual impairment had difficulty identifying the presence of openings and obstacles. Additionally, this study revealed how echolocation can help people with visual impairment to create a sense of presence in virtual worlds. Finally, study 2B

showed that people with visual impairment without previous experience with digital games saw the potential of using virtual worlds for entertainment purposes or to improve their orientation and mobility skills.

Finally, study 3 (Chapter eight) further explored how to improve the existing implementation of echolocation through a participatory design exercise. By working together with a group of expert echolocators, this study presented a series of design guidelines to further improve echolocation in virtual worlds. These guidelines emphasized the importance of passive echolocation, auditory landmarks, and pre-recorded echolocating clicking sounds. Moreover, trialling some of these guidelines revealed improved ability to detect door-like openings and obstacles.

The findings of this thesis encourage HCI researchers and game designers to consider new interaction metaphors, such as echolocation, as a means to improve accessibility in digital games, and suggest the possibility of using echolocation in virtual worlds as a tool to improve orientation and mobility training of people with visual impairment. Although the studies presented in this thesis have their limitations, the findings represent a step towards the development of more accessible virtual worlds.



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