University of Bergen

Department of linguistic, literary, and aesthetic studies

DIKULT350

Master's Thesis in Digital Culture

Spring 2022

Virtual Reality for the Visually Impaired

Addressing the current problem of virtual reality to improve the future user accessibility for visually impaired people

Milosz Zygmunt Waskiewicz

Sammendrag

Denne oppgaven har som mål å belyse og beskrive hvordan det er problemer med utviklingen av virtuell virkelighet når det gjelder synshemmede. Etter å ha diskutert årsakene til hvordan og hvorfor dette er et problem, vil denne oppgaven gi noen mulige løsninger for å utvikle virtuell virkelighet til en mer brukertilgjengelig teknologi, spesielt for synshemmede. Ettersom populariteten til virtuell virkelighet øker i digital kultur, spesielt med Facebook som annonserer deres utvikling av Metaverse, er det behov for et fremtidig virtual reality-miljø som alle kan bruke. Og det er i disse tidlige utviklingsstadiene at behovet for å ta tak i problemet med utilgjengelighet oppstår. Siden virtuell virkelighet er et relativt nytt medium i digital kultur, har forskningen på bruken av synshemmede betydelige hull. Og ettersom relativt få forskere utforsker dette temaet, vil forskningen min forhåpentligvis føre til mer aktivitet på dette viktige området. Derfor har forskningsspørsmålene mine som mål å adressere de nåværende begrensningene til virtuell virkelighet, og fylle ut noen av de viktigste hullene i dette forskningsområdet. Avhandlingen min vil gjøre dette ved å gjennomføre intervjuer og undersøkelser for å samle data som ytterligere kan støtte og identifisere de avgjørende begrensningene til synshemmede opplevelser mens jeg prøver å bruke virtual reality-teknologi. Funnene i denne oppgaven vil videre adressere problemet, skape en mulig løsning og understreke viktigheten av brukertilgjengelighet for synshemmede i den fremtidige utviklingen av virtuell virkelighet. Hvis digitale selskaper og utviklere tar tak i dette problemet nå, kan vi ha en fremtid der synshemmede behandles mer likt, med teknologier utviklet spesielt for at de skal oppleve virtuelle verdener.

Abstract

This thesis aims to illuminate and describe how there are problems with the development of virtual reality regarding visually impaired people. After discussing the reasons how and why this is a problem, this thesis will provide some possible solutions to develop virtual reality into a more user accessible technology, specifically for the visually impaired. As the popularity of virtual reality increases in digital culture, especially with Facebook announcing their development of Metaverse, there is a need for a future virtual reality environment that *everyone* can use. And it is in these early stages of development, that the need to address the problem of inaccessibility arises. As virtual reality is a relatively new medium in digital culture, the research on its use by visually impaired people has significant gaps. And as relatively few researchers are exploring this topic, my research will hopefully lead to more activity in this important area. Therefore, my research questions aim to address the current limitations of virtual reality, filling in some of the most significant gaps in this research area. My thesis will do this by conducting interviews and surveys to gather data that can further support and identify the crucial limitations of the visually impaired experience while trying to use virtual reality technology. The findings in this thesis will further address the problem, creating a possible solution and emphasizing the importance of user accessibility for the visually impaired in the future development of virtual reality. If digital companies and developers address this problem now, we can have a future where visually impaired people are treated more equally, with technologies developed specifically for them to experience virtual worlds.

Acknowledgments

This master thesis marks the end of my goal of getting a master's degree in Digital Culture at the University of Bergen. A journey that took me over five years, with ups and downs, but most importantly, a journey where I met people I will remember for the rest of my life. I would like to thank some of those people in this section.

Words cannot express my deepest gratitude to my patient and supportive supervisor, Jason Nelson, who provided me with great motivation and guidance when I needed it the most. I genuinely believe that this thesis would not have been completed without him – Thank you.

Special appreciation to my parents, brother, and grandma, who always supported and encouraged me throughout this master's degree and my whole life—I would have never been where I am today without you.

Many thanks to Morten Skutle, a friend and fellow digital culture student. For your kindness, jokes, always helping me, and most importantly, dealing with my nonsense for over six years, you made University and living in Bergen easier.

Special thanks to my girlfriend Maria, for being the most supportive and caring person I know, always making me laugh, cheering me on, and being there for me no matter what.

Thanks should also go to my leaders and colleagues at ECIT Solutions DI. To my managing director Darren White for believing in me and motivating me throughout my degree. To my manager Sondre Aase, for always understanding and helping me out when help is needed. And to all of my other colleagues who welcomed me in when I just started working in the company, thank you all.

Last but not least, I would like to thank everyone who helped me write this thesis, especially the members of the visually impaired community who participated in my interviews and surveys—this research would not be possible without your help, thank you.

- Milosz Zygmunt Waskiewicz

Table of Contents

CHAPTER ONE: RESEARCH OVERVIEW

1. Introduction

My interest in this thesis started about a year and a half ago while working as an assistant in home nursing. It was a job I truly loved, as providing care and help for elderly people was gratifying; seeing how thankful they were for helping them with even the minor things always made my day better. I tried to protect their dignity and encourage them to stay as active and engaged as possible, with either other people or different hobbies that they might have. I even tried to teach many of them how to use a tablet or a smartphone to keep them up to date, quickly developing the name "IT-Boy" among my patients. However, as many of my patients were elderly, many of them struggled with their vision, often resulting in them feeling left behind as they could not complete simple tasks alone, such as their hobbies or working with a computer or a smartphone, or even go out with their friends. Their vision impairment was limiting for them. I especially remember an elderly lady who loved sewing and painting as her hobby, but as she became more visually impaired with time, these hobbies became impossible for her to do, resulting in her sitting at home, doing nothing. Seeing her and other patients being left behind in a world increasingly dominated by digital technology, strongly impacted me. And it led to me think about how other people with vision impairment might also be struggling with new technologies. Around this same time, Facebook announced that they changed their name to Meta and would be focusing on creating the Metaverse, a virtual reality space where, at least according to the press releases, everyone could meet virtually as if it was real life. And yet, I wondered, how would my elderly patients or younger people with sigh impairment experience this new world? Interacting with people not feeling included because of their vision impairment and Facebook's announcement of creating a digital revolution where everyone would have to use virtual reality goggles to interact led me to write this thesis.

Before reading this paper any further, whether it is on a computer screen or a physical form, please close your eyes and try to read the rest of it without opening them. Without any tools to help you with reading, this task becomes impossible. Even if you keep your eyes open and only make your vision deliberately blurry, it will still be an impossible task for you to finish reading this paper. Yes, there are tools you can use, such as text-to-speech and other technologies. But, still the difficulties are real and continuing, and circumstances like these are a daily occurrence for people with vision impairments, where their vision loss and a small number of accessibility tools limit their ability to accomplish tasks that non-impaired people can complete without any difficulties. These limitations continue to rise alongside the technological growth in the society, as the consideration for incorporating the usability is often overseen in HCI (human-computer-interactions).

With the continuous development of technologies in virtual worlds, such as the Metaverse, a typical pattern for the accessibility of technology for visually impaired people has been forgotten. Often there is little to no ability-based designs being implemented from the first stages of developing these technologies, resulting in the visually impaired community always having to play the “catch up” game. Small patches of accessibility are then slowly being implemented for them to eventually catch up to a state in using computers, phones, or social media to the same extent as visually abled people.

And, as this thesis will explore and discuss, history might be repeating itself, with Virtual Reality (VR) technologies seeing a significant rise in popularity among users, developers, and companies. Virtual worlds, as a technology, still has the potential to develop and include user accessibility for visually impaired people before it is fully adopted across institutions and developers. To do this ,they must include visually impaired people from the start.

However, as this thesis will show, the development and research of user accessibility in virtual reality has not seen any consideration by the mainstream developers or companies, meaning that the difficulties visually impaired people faced during the development of computer technologies could become the same problem in the development of virtual reality. This quickly becomes a concern as one of the biggest companies in the world *Meta Platforms Inc.*, more commonly known as *Facebook*, has announced its plans to integrate virtual reality as their crucial technology for their upcoming *Metaverse*.

If Meta is successful with virtual reality, a technology with minimum usability considerations for visually impaired people, it can potentially become one of the main ways of communicating and working in social aspects with other people. The consequence results in the exclusion of visually impaired people, as the development and focus on user accessibility is far too small. A situation could arise where virtual reality focuses strongly on what is essential for visually able people, with few additional features and tools for the visually disabled. This can result in virtual reality becoming a worldwide technology for “normal” people but inaccessible for the visually impaired.

Therefore, it is essential to address the accessibility limitations for visually impaired people in virtual reality. By addressing the limitations of visually impaired users and creating studies and possible solutions to resolve these limitations, digital developers and companies can ultimately create a technology that can be used equally by visually impaired people as by visually abled people.

I will first go through the current literature about virtual reality and visual impairment to address these limitations. I will present the current problems and limitations that visually impaired people face in virtual reality. To further support the literature and understand the problems, I will be conducting interviews and surveys with visually impaired people. By doing so, I will identify the main inaccessibility for visually impaired groups, which will allow me to introduce possible solutions to create a more accessible virtual reality experience.

1.2 Research Question

The primary research question to guide this thesis is “How to make virtual reality more accessible for visually impaired people. – *Addressing the current problems and limitations for the visually impaired in virtual reality*” This research question asks for a solution to a problem; thus, I will be answering the overarching question by composing a problem-solution format for this thesis by researching literature and creating interviews & surveys to underline the answers to the research question. To do so, I will be answering specific secondary questions that focus on virtual reality, which also further helped me to crate and underline the interview & surveys. By answering the secondary questions, I will exclude the lack of information in current literature and research about user accessibility in virtual reality for visually impaired people. The secondary research questions which I will be answering throughout this thesis are:

- What are the different accessibility needs for different groups of visually impaired people?
- How does the lack of user accessibility impact visually impaired people? In aspects of technology use and social inclusion.

- What viable solutions have already been created? How can these solutions help visually impaired people use virtual reality? Moreover, how can future virtual reality technology developers benefit from these already presented solutions?

To answer the following research questions, I will be conducting an interview and two surveys based on my literature review to gain answers directly from visually impaired people. I will be framing my findings based on two major theoretical frameworks, critical disability theory, and design-in-use theory. With a combination of these theories, my interviews & surveys, and based on already existing research, I will answer the research questions. I will try to provide a comprehensive overview of the current problem with accessibility in virtual reality for visually impaired people and present possible solutions to improve the quality of use for the visually impaired, both the low-vision and fully blind groups.

1.3 Interviews & Surveys

To help me answer my research question, I conducted interviews and surveys with visually impaired community members to better guide me in their needs for user accessibility in virtual reality. Firstly, after gathering the research needed from the literature review, I conducted three interviews with participants who have different visual impairments from each other. The interviews provided helpful information as I managed to better understand the current accessibility problems from a visually impaired perspective. In addition, the information gathered from the interviews allowed me to narrow down more specific questions introduced in the surveys. Finally, the two surveys pursued to collect as much valuable data as possible, showcasing the current user accessibility limitations for visually impaired people and the aspects of accessibility that they find helpful, resulting in providing information about the aspects that work and those which do not. The gathered data will aim to support the literature presented in this thesis and provide the reader with a clear presentation of what user accessibility is crucial for visually impaired people.

1.4 Theoretical Framework

I used the critical disability theory and design-in-use theory to analyze and guide my thesis. These are theories focusing on visual impairment and its impact on people in the digital society. It is essential to include these theories, as the design-in-use theory underlines the importance of having visually impaired people involved in developing and providing feedback about accessibility in virtual reality. Furthermore, the critical disability theory looks at the social norms and social conditions of disabled people and how it teaches society to view and treat the visually impaired community, often leading to the disabled people being treated differently compared to the non-disabled.

Critical Disability Theory

Disability studies are one of the fastest-growing sections of media and cultural studies (Ellis and Kent, eds, 2017). Thus, creating the *critical disability theory* centered on understanding the political, cultural, and intellectual re-evaluation of explanatory paradigms that focus on disabled people's experiences and the possible social, political, and economic changes (Meekosha & Shuttleworth, 2009). As the critical disability theory aims to understand the cultural and social experiences, it becomes a valuable theory when researching the postmodern-virtual reality-focused world, according to Tobin Siebers, co-chair of the Michigan University's Initiative on Disability Studies (Siebers, 2008). The critical disability theory centers thus on the inclusiveness of disabled people in the social environment, a norm that "ignores differences," according to Dianne Pothier's book *Critical Disability Theory* (2014) –often making participation impossible for people with disabilities. The visually impaired people are thus often excluded from using virtual reality technology as it is designed for non-disabled people. Pothier further describes the scenarios where technology is designed for non-disabled rather than both disabled and non-disabled as a "hierarchy of difference" (Pothier, 2014). Dan Goodley (2012) describes such differences as "the oppression of disabled people pertains to those moments when they are judged to fail to match up to the ideal individual" (Doodley, pp. 639, 2012), implying the differences between disabled and non-disabled people. Mintz (2002, 162) further supports this by acknowledging the discourses around disability not being centered on the disability at all but rather by guaranteeing the privileged status of the non-disabled people (Mintz, 2002). In the case of the paper's research, Maintz's comment can be related to virtual reality technology being valued more as a creation for non-visually impaired people than visually impaired ones. To further acknowledge the hierarchy of difference, the critical disability theory does not only ask the question of "what is to be done" but also, "who is it to do it?" (Pothier, 2014). When a barrier is socially created, such as the lack of user accessibility for visually impaired people in the use of virtual reality, in which the technology is chosen to be used by the society, directly or indirectly, causes the responsibility and accountability of the lack of user accessibility for visually impaired people to fall upon the creators of virtual reality. There are multiple factors implying why technologies are not designed and developed with disabled people in mind. However, one aspect of the critical disability theory that is notably accurate for this paper, is Pothier's "question of political and power(lessness), power over, and power to" (Pothier, 2006). In the case of virtual reality for the visually impaired, the lack of disabled people in "power" correlates to a lack of visually impaired people included in the development and design of virtual reality technology. This results in non-disabled people in "power," developing and designing products created for their use, often overseeing other groups, such as the visually impaired, resulting in the current state of virtual reality lacking substantial user accessibility needed to create an inclusive experience.

Therefore, the critical disability theory will be a theory used in this thesis to understand the differences between non-visually impaired people and visually impaired. This theory aims to identify how virtual reality is designed more in the mind of non-visually impaired people, thus resulting in a significant lack of user accessibility, and how the lack of including user accessibility for visually impaired people affects them. In addition, this theory will showcase the result brought by the development of virtual reality without the inclusion of visually impaired people.

Design-In-Use Theory

Design-in-use theory looks at how products, such as virtual reality, are designed according to personal needs and practices beyond the original design thought. Thus, the design-in-use involves unanticipated users utilizing their product, which in this paper's case is virtual reality designing its technology more towards the visually impaired people as it is becoming more popular among the public. Therefore, it is transforming the structure and characteristics of the product to better suit each individual. Most notably, the design-in-use theory focuses on users adapting to the technology, its capabilities, and the design process behind the technological inventions, according to Jannie Carroll from The University of Melbourn and her *Completing Design in Use: Closing the Appropriation Cycle* paper (Carroll, 2004). This theory is essential for this thesis, as it values the importance of virtual reality design, both in the early stages of design and in the scenes where users need to adapt to using virtual reality, something showcased in the solution chapter towards the end of this paper.

1.5 Research Value

The development of virtual reality, especially now with interest from Meta, has become a technology that potentially could become the new way of communicating and interacting with people. However, there are gaps in the current research and literature that do not consider visually impaired people and their accessibility needs in virtual reality. Most studies look at creating the most immersive virtual reality experience for non-visually impaired people. In addition, the number of research done on user accessibility in virtual reality for visually impaired people is significantly small compared to non-disabled people, leading to a possible problem concerning how developers value user accessibility. Therefore, it is essential to look at user accessibility for visually impaired people and address the current problems and limitations to which they face while using the current state of virtual reality. More specifically, the lack of focus on user accessibility will decrease the usability of virtual reality. For example, suppose this technology becomes as popular as computers or mobiles. In that case, the impact of missing accessibility will have tremendous consequences on visually impaired people, a consequence that can already be seen in the current state of virtual reality. These are complex issues that need to be further explored and identified; this thesis will identify the current problem and provide a possible solution to close down the research gaps and recognize the importance of user accessibility.

1.6 Thesis Structure

This thesis is organized as follows: Chapter 1 introduces the research topic by presenting the area of interest, raises the research questions and theories that guide the thesis, and presents the value and importance. Chapter 2 is the literature review chapter, in which I will firstly present the literature about what virtual reality is. The history in the past ten years, the definitions, the technical aspects of how virtual reality works, and why it is essential to showcase these aspects in-depth based on its use for visually impaired people. It is necessary to introduce these aspects and showcases the design for non-visually impaired people and the problems which occur by developing the virtual reality technology without the visually impaired and user accessibility in mind. The 2nd chapter will also introduce the possibilities of virtual reality for visually impaired people to strengthen the importance of why creating an accessible VR for visually impaired people is so important. The terms and extent of user accessibility will also be presented in chapter 2. It is an integral part of the problem and solution of creating a more accessible virtual reality for visually impaired people. Towards the end of chapter 2, I will present some of the current problems which visually impaired people face while using virtual reality. Then in chapter 3, I will be presenting my methodology for gathering data to further support and showcase the limitations of virtual reality for visually impaired people by using interviews and surveys. In the 3rd chapter, I will introduce the decisions I took to collect the data and how they strengthened my research question. The 4th chapter will present the data collected using interviews and surveys and analyze the data to further support my thesis. Thus, chapter 4 further supports the literature review with data collection. Finally, I will present chapter 5 as possible solutions to the problems based on research and studies created in virtual reality for visually impaired people. I am then ending the thesis with chapter 6, a conclusion chapter, a summary of my thesis, and a problem-solution structure that answers my research question.

CHAPTER TWO: LITERATURE REVIEW

2.1 Introduction

This chapter presents the literature review for virtual reality, the visually impaired, and the other scholarly sources surrounding the topic. The literature review aims to provide an overview of current knowledge around accessibility for visually impaired people using virtual reality and the gaps that might result in virtual reality being inaccessible. Throughout the chapter, I will present the importance of accessibility for visually impaired people, how they can benefit from an accessible virtual reality, and the current limitations. By identifying the importance of accessibility and the current problems, this chapter will showcase the importance of addressing this topic. Furthermore, this chapter will be the crucial representation of the current "problem" part of this thesis, which builds upon the data collection in chapter four, and the possible solutions in chapter five as a response to the problems and limitations presented in this chapter.

2.2 What is Visual Impairment?

To answer my research question and create the thesis structure, an introduction of the focus group will be presented in this section. This section aims to provide the reader with a better understanding of the visual impairment, mainly divided into two groups which will be used throughout this paper; low-vision and fully blind. A detailed description of these two terms will be presented later in this section. By describing the terms, this section aims to showcase the limitations visually impaired people interact with while using virtual reality. By doing so, a difference between low-vision and fully blinded people can be identified, leading to a better understanding of what user accessibility solutions need to be provided to better their experiences in virtual reality. In addition, this section will showcase how severe visual impairment has become and thus why it needs further addressing, as it is becoming a more important topic in virtual reality.

According to the Kids Health Organization, "*Visual impairment is a term experts use to describe any kind of vision loss, whether it's someone who cannot see at all or someone who has partial vision loss* "(kidshealth.org, 2022), which means that people who either only have slight vision loss or complete vision loss, will both get classified as visually impaired. There are many different vision impairments, such as short and long-sightedness and cataracts, commonly described as a gray area in the eye decreasing vision. Other terms such as glaucoma, which is the world's leading preventable cause of blindness, an eye condition that dames the optic nerve (Armstrong, 2009), or color blindness, affecting more than 300 million colorblind people in the world, according to the *Clinton Eye Associates* (Clinton, 2022). More about color blindness and other conditions will be presented later in this chapter. According to the *World Health Organization (WHO)*, these types of visual impairment can be categorized into distance vision impairment and *Near vision impairment*. Distance has a classification of visual acuity ranging between mild, moderate, severe, and blindness. While near vision is portrayed as "*a person's experience of vision impairment varies depending upon many different factors. This includes, for example, the availability of prevention and treatment interventions, access to vision rehabilitation (including assistive products such as glasses or white canes), and whether the person experiences problems with inaccessible buildings, transport, and information.*" (WHO, 2021). These two groups are also often classified as "low vision" or "legally/severe blind." The World Health Organization classifies 'Severe' vision impairment as acuity lower than 6/60 to 3/60, and 'Blindness' as acuity lower than 3/60 (WHO 2019b). In addition, it is estimated that 2.2 billion people have some form of vision impairment (WHO 2019), with 237 million of these falling under the category of moderate to severely impaired (Adelson et al. 2020). These sources prove that visual impairment is a disability impacting a significant number of people, therefore portraying the importance of developing technology that is accessible for this amount of people. Naturally, not all of the 2.2 billion people will be using virtual reality; however, with the VR's popularity increasing, the number of visually impaired people using virtual reality is rising too, thus requiring further development of accessibility tools.

The rising popularity also contributes to the critical disability theory that underlines the importance of visually impaired people being included in virtual reality design. With the significant number of visually impaired people, visually impaired people's need to design technologies such as virtual reality is also rising.

As mentioned in the introduction of this chapter, visually impaired people can either be born with vision impairment – called congenitally blind. Alternatively, vision impairments can also be developed later in life, commonly due to an accident, trauma, disease, or medication – called adventitiously blind (Vision impairment, 2022). It is essential to distinguish the difference between these two categories in the concept of virtual reality, as people with congenital blindness and adventitious blindness can perceive the use of virtual reality differently, even though both groups are visually impaired. For example, learners who are congenitally blind may find it more challenging to make sense of virtual reality than adventitiously blind learners, who have perhaps used virtual reality before becoming blind, or other technologies similar to VR. Another important note when discussing visual impairment is how extensively it can vary, which will be underlined in this paper *survey* and *interview* conducted with visually impaired people with degrees of sight impairments. With a broad distinction made between blind people and low-vision people, each group has different limitations, study patterns, and difficulties, resulting in different kinds of support and user accessibility tools and features needed for each of them.

Therefore, the difference between "low-vision" and "fully blind" groups of visually impaired people will be occurring throughout this thesis and in my interviews and surveys. I will be showcasing the problems, answers, and possible solutions for each group throughout this paper.

2.3 What is Virtual Reality?

2.3.1 Introduction

In this section of the literature review, I will be presenting what virtual reality is by introducing how academic sources define virtual reality. This section will also include a brief introduction to the history of virtual reality as we know it today. It will create a better understanding of the current history that results in the importance of this thesis's topic and the future of virtual reality. This section in the literature review will also present the components that make up the virtual reality technology, such as head-mounted displays, controllers, and the experience visually impaired people have with the components. Furthermore, I will present the possible use of virtual reality technology, showcasing that VR has potential in more fields than video games, thus raising the importance of creating an accessible experience for visually impaired people. After reading this section, the reader should acquire an understanding of how virtual reality works, which will later on in this chapter be tied into how this technology can be limiting for visually impaired people, and the solutions for these limitations.

2.3.2 Definitions and Terminology of Virtual Reality

This section will define the term "virtual reality" to ensure that the reader understands the main component of this study. Defining virtual reality is essential as it is a technology with an extensive history, and the recent years have seen a significant development of virtual reality. By defining the term and its components, this section aims to construct a better understatement of the technology and this thesis's focus. Furthermore, by explaining virtual reality, the reader of this thesis will have an easier task of understanding the reasoning behind the problems and solutions presented later in this paper.

Academical sources define virtual reality differently depending on the interpretation that people and groups have of it, different ideas, and points of view about what it all encompasses. For example, Gulrez, a researcher in computer, science, and engineering, in his book *Advances in Robotics and Virtual Reality*, describes virtual reality technology as a "use of graphics systems in conjunction with various display and interface devices to provide the effect of immersion in the interactive three-dimensional computer-generated environment, which is called a virtual environment." (Gulrez, pp 363. 2012). Immersion refers to the objective feeling that virtual reality systems provide, as described by a professor of computer science at Virginia tech, D. A. Bowman, and his Ph.D. candidate R. P. McMahan, in *Virtual Reality: How Much Immersion Is Enough?* (D. A. Bowman and R. P. McMahan, 2007). This feeling of immersion can be achieved through different methods, presented later in this chapter.

Furthermore, Henry E. Lowood, from Sanford University science and technologies, defines *virtual reality* as the "use of computer simulation that enables a person to interact with artificial three-dimensional visual or another sensory environment" (Lowood 2021). In chapter five, *solutions*, an example of interacting with the virtual reality environment for fully blind users, will be presented. In addition, the Virtual Reality society defines VR technology as computer-generated imagery and hardware specifically designed to bring together sight and sound, resulting in total immersions (Virtual Reality Society 2019). This definition can be problematic, as the use of sight is limited for visually impaired people; thus, the importance of sound will be presented throughout this paper.

In addition, Peter Rubin, a contributing editor, defines virtual reality in his book How Virtual Reality is Changing Human Connection. Intimacy and the Limits of Ordinary Life define *Virtual Reality* as: "an artificial environment that's immersive enough to convince you that you're actually inside it." (Rubin, pp.27, 2018).

These definitions define virtual reality as an immersive environment created by multiple factors such as sight and sound; these and more factors will be described later in the chapter. In conclusion, virtual reality is a computer-generated environment set to create a virtual space, often a copy of a real-life place, inside a computer. The user will be able to access and control through a set of hardware, such as goggles and input devices, to a point where it feels immersive, meaning that it feels like a real-life place. Throughout this paper, I will be discussing how to create a more accessible virtual reality, thus the feeling of immersiveness. In addition, the data collected from the surveys in chapter five will present how important the sense of immersiveness truly is for visually impaired people.

2.3.3 History of Virtual Reality

In this section, I will present the history of virtual reality. However, as the history of virtual reality is long and detailed, it naturally provides information that is not necessarily impactful for this study. Therefore, this section will only introduce the beginning of virtual reality in the '60s; then present the valuable history of the current state of virtual reality that formed the rise of popularity as known today. The current history is still young, as virtual reality development is relatively new, hence why this study is essential. It still leaves significant space for "new" history, where user accessibility for visually impaired people is included. It is essential to include the history of virtual reality, as we can look back upon the early years of development of this technology and tie both leading theories of this thesis into it. Looking at the history may explain that the current state of virtual reality for visually impaired people is still lacking in its current form. The contemporary history also depicts the reasoning for this research study, as Metaverse is writing the recent history for virtual reality and potentially for visually impaired people. However, if it is going to be a positive or negative future is something this study will try to answer.

The Beginning

Virtual reality's history goes as far back as the '60s when Ivan Sutherland presented his first idea of virtual reality in 1965: "make that (virtual) world in the window look real, sound real, feel real, and respond realistically to the viewer's actions" (Sutherland, 1965). Sutherland's idea has not come this far yet, but considerable progress has occurred. With the rapid development of technologies, his idea of what virtual reality could be might come true sooner than one could anticipate. Sutherland did not create only ideas; he also made virtual reality systems. His ***Sword***

of Damocles was one of the first virtual reality systems realized in hardware, not only in concept (Sutherland, 1968). This technology consisted of complicated and unwieldy goggles hanging from the ceiling. The user of these goggles had to step *into* a set of hanging-down rudimentary computer screens to display a transparent cube (Sutherland, 1968). Recent history has come a long way since the invention of Sutherlands' idea, and the hanging-down goggles are no more than history for today's virtual reality. However, several aspects can still be seen as inspired by the early virtual reality.

The Current History

In the last three decades, the creation of virtual reality technologies had an essential effect on the virtual reality known today, and virtual reality has come a long way since then. The concept of virtual reality that we best know today saw its significant growth in popularity in the mid-2010s. This spark of rage started in 2012 with a successful Kickstarter campaign, a website where creators can collect funding for their projects, and where the public found interest in the Oculus Rift, founded by Palmer Luckey (Kickstarter, 2016). Oculus Rift quickly became the talking point in the media, describing the product as potentially the first immersive virtual reality headset and a way of stepping into the game. The hype around Oculus accumulated an astonishing $2.4 million from the Kickstarter campaign (Kickstarter, 2016). Two years later, Facebook bought the Oculus VR company for $2 billion, a defining moment in VR's history, quickly sculping the virtual reality that we know and use today (Luckerson, 2014; Castelvecchi, 2016). The purchase by Facebook has a substantial effect on the current situation for virtual reality, presented later in this chapter.

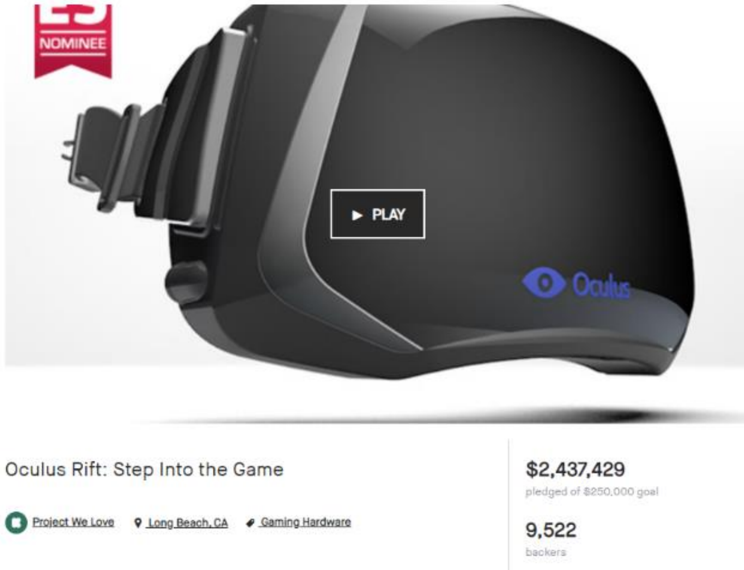


Figure 2.1 - “Frontpage for the “Oculus Rift: Step Into the Game” Kickstarter” (Kickstarter, 2016)

As the popularity and advancements in technology developed, virtual reality became more obtainable for everyday users, and with the user-marked growth came the developer interest from various companies. As a result, by 2016, hundreds of companies were starting to develop VR products, and by 2016 the biggest companies in the world were invested, such as; HTC, Google, Apple, Amazon, Microsoft, and Samsung (Korolov, 2014; Ebert, 2015; Castelvecchi, 2016), started to develop their products for VR (Veer VR Blog, 2022).

One of the main reasons this chapter reviews history is its potential outcome on visually impaired people, further supported by the *critical disability theory* and *design-in-use* theory. Firstly, the early development by a minor team in Oculus Rift founded by Palmer Luckey most likely did not highly focus on visually impaired people, which further supports the *critical disability theory*, which focuses on visually impaired people's involvement in the early years' stages of development. Without insightful information from visually impaired individuals, the Oculus Rift team most likely purely concentrated on developing a technology worth publishing for the mass media, in which visually impaired people and their needs for different accessibility features were often forgotten. With the additional publicity around the first creation of Oculus Rift and the rapid development from the biggest companies in 2016, as previously mentioned, one could argue that *critical disability theory* took place. With the lack of user accessibility focus, which examples of will be shown later in this chapter, the developed virtual reality was developed for visually abled people. Thus, visually impaired people have to adapt to that specific design, often inaccessible, creating a less immersive, accessible, and generally less functioning virtual reality experience. Therefore, it is essential to address the technical terms of virtual reality and see how these are designed primarily for visually abled people. Pothier (2006) points out "people in power" in the *critical disability theory*, which further supports how the lacking the involvement of visually impaired people in the early stages of development affects the rest of the technology and visually impaired people—resulting in limitations that will be presented later in this chapter.

2.3.4 The Technical Terms of Virtual Reality

This section will present the multiple technical terms that create virtual reality. These are technical terms that determine how virtual reality can be interacted with in real life, such as how VR is consumed or controlled, with the addition of the aspects which work to create the virtual experience as immersive as possible. These terms are often designed with abled people in mind, resulting in hardware that visually impaired people can find limiting. The terms and the hardware presented in this section are; *Stereoscopic displays, motion tracking, input devices, desktop & mobile platforms, spatial audio & sound effects, and haptic & force feedback.* It is essential to introduce these terms and hardware aspects of virtual reality, as this thesis will present the problems and solutions in which each of these terms and hardware are introduced.

Virtual reality is a technology created with multiple components designed to transform the user's experience in different ways, all combined to create the possibility for complete immersion in the virtual environment (Bardi, 2022). Gulrez's definition of virtual reality showcased just how technologically advanced virtual reality is "graphics systems in conjunction with various display and interface devices to provide the effect of immersion in the interactive three-dimensional computer-generated environment" (Gulrez, pp 363. 2012). Gulrez's definition means that virtual reality is about feeling like the user is somewhere else. Through hardware and software, virtual reality enhances the user's involvement in a more or less immersive and interactive virtual human experiment (Schultheis, 2001). We often achieve the feeling of getting immersed into an environment daily; watching a movie is an excellent example of that, in which the focus and state of immersiveness often give the sense of "being in the movie" despite only sitting in front of a TV or theater screen. Virtual reality achieves that feeling by tricking the human brain – particularly the brain part that perceives motion, the visual cortex. To fully "trick" the brain, few can examine Tony Parisi's example in his book *Learning Virtual* Reality (Parisi 2016), where he mentions a variety of technologies that are combined to create a fully immersive virtual reality experience, those being the following:

Stereoscopic Displays

Virtual reality relies heavily on converting the virtual experience through a visual display, with the visual screens displaying the content. Thus, being a limitation for visually impaired people, as the main feature providing the content, goes against heavily the visual impairment disability; understanding what stereoscopic displays are is thus essential, as it is the main limitation for visually impaired people.

Stereoscopic displays are mainly known as *head mount displays* (HMDs) or *3D displays*, being the VR headset/goggles in the context of virtual reality. “These displays use a combination of multiple images, realistic optical distortion, and special lenses to produce a stereo image that our eyes interpret as having three-dimensional depth” (Parisi 2016). The *A Review Paper On Oculus Rift & Project Morpheus* study by Goradia, Doshi, and Kurup (2014) mentions that today’s mainstream virtual reality headsets utilize two lenses to create stereoscopic 3D imagery creating depth and, as Parisi mentioned, tricking the brain into perceiving realism.
A persistent 3D visual representation is the main component in conveying a sense of depth for virtual reality users. Hardware systems create depth in virtual reality, most known as *head-mounted displays* or *stereoscopic displays*. However, terms such as *VR headsets or goggles* are also used.

Figure 2.2 - The Oculus Rift Head-Mounted Display, Development Kit 1 (vrcompare, 2022)

As previously mentioned in this chapter, virtual reality achieved its popularity in the mid-2010s when the team from Oculus VR developed the *Oculus Rift* (Kickstarter, 2016). Before the invention of *Oculus Rift*, the most major hindrance to consumer-grade virtual reality where the need for a light and comfortable enough stereoscopic display that could be worn for an extended period, something that *Oculus Rift* nourished. Determining how virtual reality could be consumed and used sets off a spark for the VR development that can be experienced today. The hardware used in the first *Oculus Rift*, known as the DK-1 (Vrcompare. 2022), has seen significant growth, already in the 2nd version of the *Oculus Rift* development kit. The technologies such as display resolution, position, and orientation tracking improved, resulting in an improved virtual reality experience.

.

Figure 2.3 - The inside of a stereoscopic display (Roadtovr, 2013)

Stereoscopic displays in virtual reality generate a separate image for each eye while being slightly offset from the other. Creating the illusion of depth, also known as the *parallax*, is described *by* Parisi as “a visual phenomenon where our brains perceive depth based on the difference in the apparent position of objects (due to our eyes being slightly apart from each other).” (Parisi 2016). Visual perception is a critical factor in experiencing the illusion of depth through a virtual reality headset. The headset relies heavily on the user’s vision compatibility, with the two lenses being positioned near the eyes. Figure 2.3 shows how a VR headset looks from the inside; the foam around the headset covers the face and eliminates any source of light coming through, allowing the user to fully interact and immerse themselves into a simulated environment and experience the virtual reality considerably close compared to the non-digital reality.

With the shift towards more wireless headsets and technological advancements in resolution, color, and head tracking, virtual reality has gained considerable momentum in the market (Rogerson 2021) (Feltham 2019). With the current technological advancements, and especially the way it is heading, these wireless displays are becoming more standard among people, with more affordable alternatives and better hardware continuously placed on the market. Unfortunately, this has not always been the case, as the hardware of previously mentioned resolution, color, and head tracking did not allow the creation of a resalable headset (Murphy 2016).

As the stereoscopic displays are the primary way of interacting within the virtual environment, it is naturally the main limitation for visually impaired people. Not involving visually impaired people in the early virtual reality design and development affects visually impaired users. The limitations and how they can be addressed will be presented later in the paper, with the surveys going in-depth about the limitations of using a stereoscopic display to display content for visually impaired people.

Motion Tracking

Like the stereoscopic display, another form of interacting with virtual reality that is important to mention is motion tracking. It allows the virtual reality user to use their body, head, arms, or even the whole body, to navigate the virtual reality environment (Sveistrup, 2004). For example, tracking the whole,

body's movement allows the visually impaired users to use their head movement as a tracking mimic where they move the head closer to an object, allowing them to see the virtual objects up closer.

Motion tracking hardware is a system of gyroscopes (a device used for measuring or maintaining orientation and angular velocity)(You and Neumann, 2001). Moreover, accelerometers (a device that measures the vibration or acceleration of motion of a structure) are used to sense when a user turns their body or head, resulting in the application updating the 3D space inside the virtual reality (You and Neumann, 2001).

Besides the visual orientation through Stereoscopic Displays, which create the feeling of immersion, motion tracking is combined to enhance the feel for the user by tracking the movements of the head and updating the rendered scene in real-time. Motion tracking mimics the direction of the head in the real natural world in the virtual space, meaning if the user decides to move their head forward in real life, the same movement of the head will be repeated in the virtual space. Motion tracking enables the virtual world to be less restrictive, giving the user the ability to look and move, creating a realistic perception according to our natural environment (Roetenberg, Luinge, and Slycke 2009).

Further limitations and benefits of motion tracking will be discussed throughout this paper, with an interview going in-depth about how it currently is beneficial for visually impaired people and the limitations that occur within it, showcased in chapter four.

Input Devices

As virtual reality is built upon a set of hardware devices, with the previously mentioned stereoscopic display that displays the content and motion hardware that tracks the user’s movement, the method of interacting and controlling the displayed content and movement is often done by the use of an input device. Navigating and selecting content in virtual reality, such as interfaces or objects, is most often done with input devices. The user has to point at the part of the virtual environment they want to interact with; this selection method can often be proven difficult for people with visual impairments, which will be showcased throughout this thesis.

Therefore, it is essential to address the use of input devices for visually impaired people and the possible limitations following that type of interaction to create a more accessible way of using them.

According to the literature, input devices can range from a simple joystick or a keyboard to a glove that can be worn to control the environment, as mentioned by Grigore Burdea, a computer scientist from Rutgers University (Burdea et al., 1996; Burdea and Coiffet, 2003). With virtual reality development, the input devices have evolved into handheld controllers (Figure 2.4) with motion tracking, allowing users to use their hand movements to control the virtual environment. With motion tracking, the controller is often used in virtual reality to point at virtual objects. A user often uses their arm to navigate and point at the objects, rather than using a mouse or other assistive programs that can help guide the interface or objects.

Figure 2.4 - A virtual reality controller (techooid.com, 2016)

Further examples of how input devices can be proven limiting for visually impaired people will be explained later in this chapter and further supported by the research survey in chapter four. In addition, the possible ways of implementing input devices to make virtual reality more accessible for visually impaired people will be presented in chapter five. In that chapter, I will present the *Canetroller,* a controller created to mimic a white cane used by blind people, and *SeeingVR,* a possible solution for making the current controllers more accessible using different tools incorporated into virtual reality. The *Canetroller* (Zhao, 2018) and *SeeingVR* (Zhao, 2019) are both research studies done by Dr. Yuhang Zhao. Dr. Zhao is an assistant professor in the Department of Computer Sciences at the University of Wisconsin-

Madison and will be a crucial part of this thesis chapter five. I will be presenting the possible solutions to create a more accessible virtual reality for visually impaired people.

Desktop and Mobile platforms

Desktop and mobile platforms are the platforms that run the application in virtual reality, computer hardware, software interface, operating systems, and software applications that users can use to interact with virtual reality. Mentioning them is crucial, as it focuses on developing virtual reality. Within these platforms lies the possibility of adding new accessibility products which can help visually impaired people interact in a more accessible manner. These platforms are also the stages where including visually impaired people in the development is crucial, as the *critical disability theory* indicates. One of the most popular software applications for virtual reality is *Unity VR*, "software for developing a new architecture that improves the support for existing and future augmented reality (AR) and virtual reality (VR) platforms" (Unity, 2022). Unity VR is the number one software application for developing new user accessibility tools; an example of how the visually impaired can benefit from Unity VR will be showcased in chapter five, where I introduce the *SeeingVR* concept created by Zhao(Zhao, 2019). *SeeingVR* emphasis is on using Unity VR to create accessibility tools for visually impaired people, which is essential to mention as it is a critical point for answering the research question of this thesis.

Spatial Audio and Haptic Feedback

This section will present the importance of spatial audio and haptic feedback, as these two are powerful technologies that aid visually impaired people in using virtual reality. Furthermore, both value the dominant senses of visually impaired people, and creating accessibility features based on these two terms can lead to accessibility improvement of virtual reality. Therefore, this section will describe the use and importance of spatial audio and haptic feedback.

Spatial audio and sound effects are essential enhancements for the human perception ability, especially for visually impaired users, helping them with the ability to capture and process the information received by their senses. Although the sense of sight is limited or altogether taken away from visually impaired people, "they may still compensate with enhanced hearing, taste, touch, and smell," according to a March 2017 study published in the journal PLOS One (PLOS One, 2017). Thus, it often results in audio becoming an essential sense for visually impaired users. Heilig, an American pioneer in virtual reality, writes in his study on human senses, which of the senses are contributing the most; sight is the most contributing to humans, with approximately 70% of our senses, with the sense of hearing coming in at number two with 20%. Then smell 5%, touch 4%, and taste 1%. (M. L. Heilig, 1992). Based on Heilig's study, we can emphasize the importance of spatial audio, as visually impaired people lack the most contributing sense of sight, making hearing their primary sense.

The critical factor of spatial audio for visually impaired users, and virtual reality users in general, is the perception ability of information outside of their visual display. Spatial orientation cues create additional information for the user, making it even possible for the parallel perception of many information streams (Mereu and Kazman, 1997). Sound can indicate simple things; in virtual reality, sound can indicate the completion of a task with a sound cue. It can alert the user of a collision with a sound alert or suggest that an object has been dropped or grabbed, all attainable with a straightforward sound cue. Sound in virtual reality can also display clear three-dimensional auditory sounds to simulate distance, direction, material surface, and spatial information around the virtual environment (Zhao, 2018). Spatial audio application benefits regular users by introducing information and can be even more beneficial for visually impaired users. It is often the primary sense used by the visually impaired to orientate around in the real world; therefore, not a technological feature that needs to be learned. This theory and more about spatial audio will be presented in chapter five. The paper discusses *Canetroller* (Zhao, 2018) as a potential solution where sound-generated feedback plays an essential aspect of accessibility.

Haptic feedback comprises force feedback, also known as kinesthetic, forces sensed by the muscles, joints, and tendons (O'Malley and Gupta, 2008). Moreover, tactile feedback; is feedback through the skin, such as sense of touch, texture, temperature, or pressure on the skin surface. In virtual reality, haptic feedback is distinguished through the input device used by the user and often combined with spatial audio for an immersive effect. The most common haptic feedback for virtual reality (*Oculus Quest 2*) is vibration through controllers. Users can experience the vibration by interacting with the virtual environment, with different levels of feedback depending on the program's adaptation of force feedback. An example of this could be the popular VR game *Beat Saber (*Beat. 2019). The main objective is to hit incoming boxes with a lightsaber projecting out of the controller inside the virtual environment. On impact between the lightsaber and a box, the input device *(controller)* gives out haptic feedback *(vibrations),* informing the user that a square has been hit. *A spatial audio cue is also received for additional information.* An example of how the visually impaired can benefit from haptic feedback will also be included in chapter five, where I will look at the *Canetroller*.

Both spatial audio and haptic feedback are senses well known for visually impaired people; by addressing that information and including these two terms in the development of future virtual reality, a more accessible environment and an interactive experience can be created for visually impaired people, particularly within the fully blind group.

2.3.5 Variety of Applications Creating Important Possibilities

The variety of applications that virtual reality can enable people to participate in a multitude of different activities. Virtual reality became a significantly exciting technology for the entertainment aspect of applications, most commonly known in the field of video games after the successful Oculus Rift Kickstarter. However, this has grown into a wider variety of possibilities in new and different fields to be explored.

The wider variety of options builds up virtual reality to be used by more people. With more people using the technology comes a higher need to address the accessibility requirements. Therefore, this section will present the following application for which virtual reality can be used, further supporting the research question by showcasing the possible uses for virtual reality.

Virtual reality and environment applications cover a wide range of specific applications, especially in the last decade with virtual reality growth in business and commerce, telecommunications, entertainment, and gaming to medicine. Moreover, it is a multidisciplinary technology based on engineering and social sciences, where possibilities and progress largely depend on technical developments (Gulrez, 2012). Virtual reality uses interactive simulations to create opportunities for the user to engage in environments with a level of immersion similar to the real world; these environments can be set and used in various ways in virtual reality. In addition, VR technologies can be used for other purposes, each with its pattern of showcasing the environment; Training and education, entertainment, and information retrieval are the most common areas for virtual reality. Medicine, culture, education, and architecture have already taken advantage of this technology (Iberdrola, 2022). Here are some innovative uses for VR:

Beginning with the most common use for virtual reality, which created a new era for virtual reality, **Video Games.** Focus on virtual reality development for video games is at its peak; with the potential for deep immersion, higher production value, and extensive user engagement, video games create the most significant interest. Virtual reality video games allow the user to experience and immerse themselves into a virtual world that they could never imagine in real life.

Medicine: The media do not widely cover medicine virtual reality application like video games; however, its development has reached a point where both doctors and patients can benefit from the technology. Surgical training, pain management, and therapeutic treatment of mental illness play the leading roles in virtual reality medicine (Lan Li, Q.J. 2017).

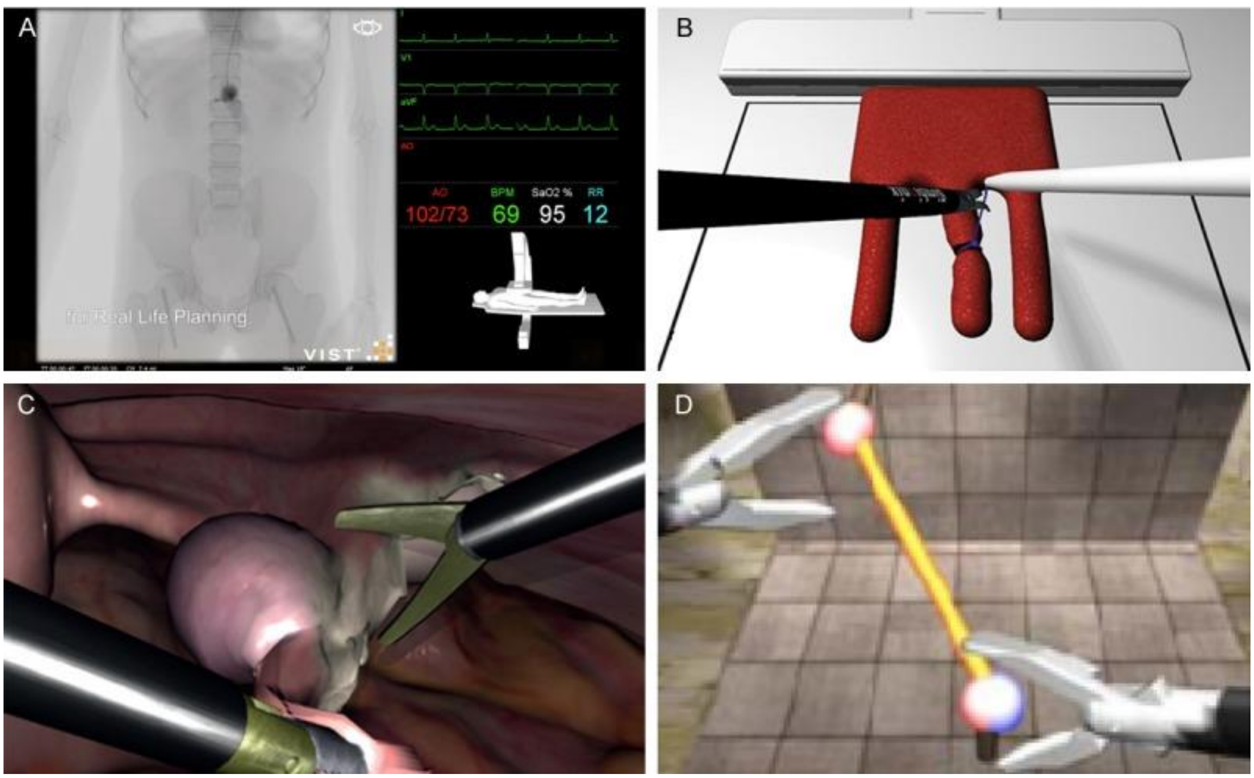


Figure 2.5 - Medical simulations in virtual reality (Lan Li, Q.J. 2017)

Figure 2.5 showcases four different medical simulations for virtual reality. MIST VR: Realistic image data and simulated vital signs (A), Lap Mentor: Basic knotting training (B), Lap Sim: Clipping and cutting off training (C), and Simendo: Stretching with misorientation training (D) (Lan Li, Q.J. 2017). The application of virtual reality for tasks like these can create a better learning experience for medical students. This example might not be focused on visually impaired people. However, it showcases the growth and possibilities of virtual reality, indicating that VR can be used for more than just video games.

Training and e-learning: These categories are similar to **medicine** since patience training can be done in virtual reality. However, training and learning can be done outside of the medical field. A perfect example of training done in virtual reality is by Dr. Yuhang Zhao, who invented a Canetroller (Zhao, 2018), an interpretation of a white cane in virtual reality created to help and learn users navigate around. It can be used for learning to navigate the virtual world and for newly blind users to learn how to navigate the real world—for example, learning how to cross a street in real life without risking the dangers of learning it in the real world, further on this technology in chapter five.

Education: It can be categorized under e-learning and includes schools, sports coaching, and programs explaining the laws of nature. The user could be placed in a natural environment they are studying, such as a hurricane or flood, without risking their life (Anderson, 1993). However, virtual universities and classroom lectures might see their most considerable potential in education, where users will be able to attend school without leaving their homes. Virtual reality education opens up for visually impaired people to participate in school-related activities if accessibility allows for it. Initially, the focus of Meta is to create virtual reality into a virtual space where school settings will be a significant focus—emphasizing the importance of developing virtual reality into a more accessible technology for visually impaired people, as the consequence of not doing so may result in lack of educational attendance.

Entertainment: Video games are a significant part of the entertainment. Still, virtual reality opens up possibilities to experience entertainment such as concerts, with *Muse,* a famous rock band, and their *Simulation Theory b*eing the most famous example. *Simulation Theory* is an interactive stadium experience where users can view the concert from 16 different angles in a fully 360 immersive environment (NME, 2021). Applications like this can allow visually impaired users to experience concerts or video games (such as driving a car), something they could find limiting them in real life.

Tourism: The stereoscopic 360 panoramas in virtual reality create opportunities to experience the world without getting on a plane (Parisi, 2015) or experience museums inside your living room. Thus, tourism could allow the visually impaired people to visit locations that would be very limiting for them to visit. An example of this could be a museum, where objects could be described or enhanced in a particular way, making the museums in real life more accessible for visually impaired people in virtual reality.

Pandemic: The 2020 COVID-19 pandemic has impacted everyone worldwide, with significant challenges posed to the education systems. Schools, work offices, organized establishments, foundations, and even societies are affected by the crisis. (Daniel, S.J, 2020). With everyone staying at home because of health regulations, digital learning formats such as asynchronous learning and remote learning became more popular among schools and offices. However, a study on the challenges of working from home by *BetterUp* in 2021 showcased that the most significant challenges were collaboration and communication with others, as well as loneliness (BetterUp, 2021). The study underlined that sitting in front of a computer screen did not give the users the same feeling as inside the classroom or in the office. With the essence of immersion and creating the feeling of being somewhere else, virtual reality could make sense of being used in the school or office environment, resulting in more prominent inclusion.

These applications describe the different scenarios that visually impaired people can benefit from and showcase the growth virtual reality has seen in the past years. A concept that started from a Kickstarter a few years ago is seemingly developing into a technology used for a magnitude of different applications. This further supports the importance of developing virtual reality into a more accessible technology for the visually impaired, as the future where VR is used for multiple applications is fast approaching. By looking at the growth, one could limit the critical disability theory, where disabled people are not considered in the development of new technologies. By including visually impaired developers in virtual reality design, these applications will have a higher focus on user accessibility and, initially, be designed with visually impaired people in mind.

2.4 User Accessibility and Technological Visual Aids

This thesis focuses on user accessibility and has already mentioned it multiple times throughout this chapter; it is essential to acknowledge what user accessibility is and why is it important for this thesis? In this section of the chapter, I will be answering these questions by presenting what user accessibility means for virtual reality, the limitations that occur for visually impaired people in virtual reality, and how user accessibility can create an immersive and valuable experience for the visually impaired people in virtual reality.

To better understand how the use of virtual reality for visually impaired users is limited, a definition of user accessibility is needed. It will provide a better understatement of the overall research question placed for this thesis. Addressing these limitations will also create framing of which accessibility points are not significant enough for visually impaired people, further supporting the research question of this thesis.

Accessibility is a concept where the product or service used by someone can be used regardless of how a user encounters it. Whether the user is non-disabled or disabled, the product or service should be designed for them to interact without limitations. Accessibility laws are created to aid people with disabilities, and accessibility has become an essential factor in design; developers and designers try to make their products and services as accessible as possible for everyone, creating what we call *inclusive design* (Clarkson, Coleman, Keates and Lebbon, 2013).

The inclusive design includes all states of disabilities, which are often categorized into three states; permanent, temporary, or situational disabilities (Haider, 2022). An example of these three inclusive design categories in virtual reality for the visually impaired could be a permanent disability, representant of blind users, and their complete loss of sight. A temporary disability could be a state after eye surgery, limiting your use of virtual reality. Then situational disability can be described as, for example, someone forgetting their glasses at home before going to work and having to use virtual reality for a day without their glasses. The inclusive design showcases why user accessibility is essential, not only for a specific group of people, such as the visually impaired but also for everyone, as it affects everyone at some stage in life.

This paper's primary focus is the permanent disability, with user accessibility designed for visually impaired users in virtual reality technology. User accessibility has rules set by the *Web Accessibility Initiative, WAI,* which ensure that *accessibility, usability,* and *inclusion* are aspects created to work for everyone when using websites and applications (W3C, 2022). The official definitions for these aspects are:

> **Accessibility***: "addresses discriminatory aspects related to equivalent user experience for people with disabilities. Web accessibility means that people with disabilities can equally*

perceive, understand, navigate, and interact with websites and tools. It also means that they can contribute equally without barriers." (W3C, 2022).

Usability*: "is about designing products to be effective, efficient, and satisfying. Usability includes user experience design. This may include general aspects that impact everyone and do not disproportionally impact people with disabilities. Usability practice and research often does not sufficiently address the needs of people with disabilities."* (W3C, 2022).

Inclusion*: "is about diversity, and ensuring involvement of everyone to the greatest extent possible. In some regions, this is also referred to as universal design and design for all".* "*accessibility for people with disabilities"* is on top of the list. (W3C, 2022).

In the solution chapter, these aspects of user accessibility will be showcased as examples of current research discussed and created as a solution for virtual reality.

Limitations of User Accessibility in Virtual Reality

To further elaborate on user accessibility, we can look at Mott et al. *Accessible by Design: An Opportunity for Virtual Reality* (Mott et al., 2019). In this study, Mott et al. describe the various accessibility fields as essential fundamentals for visually impaired people in virtual reality use. To further support accessibility, Mott et al. discuss the need, opportunities, and challenges that visually impaired people face with insufficient or fully without user accessibility (Mott et al., 2019).

Content accessibility is described by Mott to be a way in which the media have agreed-upon standards and/or guidelines to make content accessible for everyone, regardless of their disability (Mott et al., 2019). An example of content accessibility is text captions over videos, such as YouTube videos or TikTok, where a text alternative is displayed as an alternative to the sound. This benefits people with disabilities and is a part of the previously mentioned *inclusive design*, where permanent, temporary, or situational disabilities are addressed. Similar situations can be addressed for visually impaired people, with text readers or object descriptions reading aloud the objects or environment around a person with low vision. However, Mott states that virtual reality lacks the agreed-upon methods for making content accessible (Mott et al., 2019), especially for visually impaired people where screen readers are non-existent. Content accessibility is a perfect example of my leading theory of design-in-use and critical disability theory, where VR is not designed with visually impaired people in mind. Including them in VR design would most likely solve this issue. The only research that tries to solve this problem is SeeingVR, a toolset for low-vision users in virtual reality, where text-to-speech is one of the presented tools and will be explained later in this chapter (Zhao, 2019).

In addition, haptic feedback is one of the primary senses for visually impaired people to interact with different environments and objects. Unfortunately, little research has been done to implement haptic feedback into a more accessible feature for visually impaired people. However, the *Canetroller* (Zhao, 2018), which will be presented and discussed later in chapter five, has demonstrated how rendering virtual objects haptically are possible. *Canetroller* successfully simulates different materials, properties, and textures, allowing fully blind users to navigate the virtual environment with their real-life white cane techniques (Zhao, 2018). However, the current state of haptic feedback is at a bare minimum for user accessibility help and a challenge for blind people.

Therefore, Mott states that there is a problem that needs identifying, in addition to a multimodal representation of the virtual reality content so everyone can use it, no matter the disability (Mott et al., 2019). If the design-in-use theory gets implemented to develop these devices further, a more inclusive and precise identification of the problem will be obtained. Mott also mentions a solution of including the already existing and well-proven device accessibility into virtual reality; desktop and mobile device accessibility. If fully transferring these into VR is not possible, at least learning from what already works will still provide positive changes for device accessibility in virtual reality (Mott et al., 2019).

Interaction Accessibility intends to create the most immersive environment for the user through hardware, as mentioned earlier in this chapter: stereoscopic displays, motion tracking, audio, and haptic feedback. Mott et al. (2019) present interaction accessibility as something which can bring multiple positive outcomes in the future; however, it may also be significantly limiting for people with disabilities. An example is a coloration between computers and VR today, where computer-based accessibility is more giving than virtual reality, hence why virtual reality needs to account for end-user diversity (Mott et al., 2019).

VR User Interfaces are presented by Mott as one of the most significant limitations, which large differences from virtual reality interfaces to computer interfaces (Mott et al., 2019). Examples of these limitations will be presented further in this chapter. One of the most significant limitations found in virtual reality interfaces is their 3D interfaces, creating them more towards feeling the immersive rather than the practicality of an interface, which often is limiting for visually impaired users. To further support this study, Mott underlines the need to conduct formative studies to understand and develop virtual reality for visually impaired people into a more accessible medium (Mott et al., 2019). Formative studies such as Balakrishnan, R. *"Beating" Fitts' law: Virtual enhancements for pointing facilitation* (Balakrishnan, R. year?) or Wobbrock, J.O. et al. *The Angle Mouse: Target-agnostic dynamic gain adjustment based on angular deviation* (Wobbrock, J.O. 2009), which are studies that focus on providing additional stability and control by relaxing the need for precise pointing, which could make virtual targets easier to select by increasing their size in motor space.

Device Accessibility, defined by Mott et al. (2019), is about how the devices are built, with a stronger focus on mobility disabled people. However, an example of device accessibility is *Canetroller* (Zhao, 2018), showcased later in chapter five. *Canetroller* is a white-cane controller for blind users to navigate virtual reality similar to navigating the real world (Zhao, 2018). However, it is a device built with several components, thus potentially being clunky, with possible limitations if a blind user were to set it all up for themselves. Examples like that prove the importance of device accessibility for the future, as the *Canetroller* device or similar device could become a more reliable and standard tech. Nevertheless, a stronger focus on this part of accessibility is needed for it to happen, which also further supports both of my guiding theories in this thesis. Critical disable theory shows that devices are not made for visually impaired people. The design-in-use theory showcases the importance of including visually impaired people in the design of these devices from the early stages.

2.5 What is Metaverse?

As mentioned previously in the current history section, the Oculus Rift was bought by Facebook for two billion dollars (Luckerson, 2014; Castelvecchi, 2016), and now is planning to create a so-called Metaverse. In this section, I will be describing what Metaverse is, as it is both a crucial part of my thesis and the virtual reality world for visually impaired people. Furthermore, it might be setting a new standard of how virtual reality will be used, thus also introducing the importance of addressing user accessibility before it is too late. Thus creating an example of critical disability theory where history repeats itself and the new technology of virtual reality is not developed with visually impaired people in mind.

Initially, one of the main reasons for my interest in writing this paper was the hype around Metaverse, especially after Mark Zuckerberg, Co-founder, and CEO of Meta Platforms (formerly Facebook, Inc.), announced that Facebook would be changing its name to *Meta*, and focus significantly on interpreting the virtual reality into their future. *Meta* describes the Metaverse as follows:

"*The "metaverse" is a set of virtual spaces where you can create and explore with other people who aren't in the same physical space as you. You'll be able to hang out with friends, work, play, learn, shop, create, and more. It's not necessarily about spending more time online — it's about making the time you spend online more meaningful.*" – Meta, 2021.

Metaverse emphasizes what this paper mentioned earlier in the ***Pandemic*** section, that working remotely from home is becoming more available with the technology development. In addition, the Metaverse can create a more immersive and inclusive environment through virtual reality.

"*The way we work is changing. More people are working remotely, more people want flexible work options, and more people are re-thinking what it means to be in an office. But without the right connective tools, remote work still has plenty of challenges. Working without colleagues around you can feel isolating at times. and brainstorming with other people just doesn't feel the same if you're not in the same room."* – Meta, 2021.

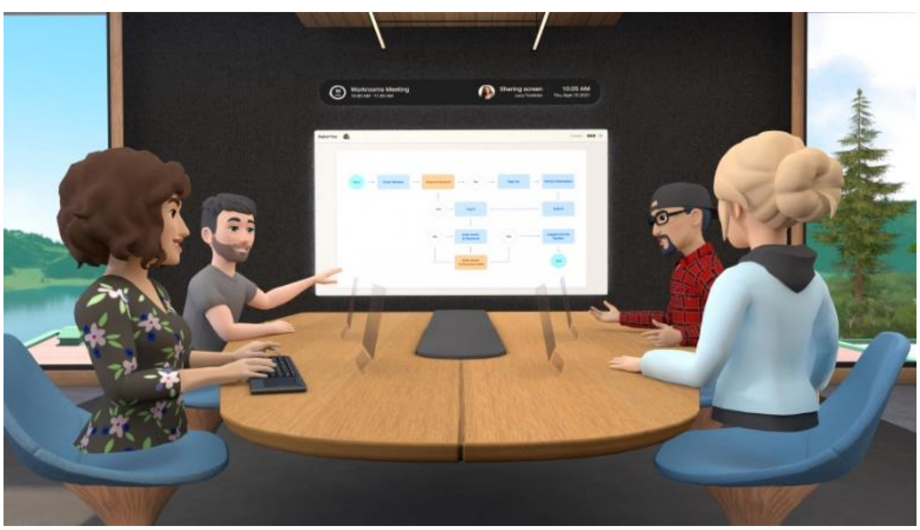


Figure 2.6 - A Metaverse work environment (T3, 2022)

Figure 2.6 "*Workroom" is a Metaverse office meeting room where users can immerse themselves into feeling like they were in an office meeting room, all inside virtual reality.*

Metaverse will be a virtual space where users can socialize, learn, collaborate, and play in ways that go beyond what we can imagine (Meta, 2021).

The Metaverse is believed by many to be the future of how we live our daily lives; the theory for Metaverse is an accessible environment where users will be able to communicate with each other as if they found themselves in a real-world setting. However, the developers of Meta underline that the Metaverse is not something built overnight, and many of their products will be fully realized in the next 10-15 years (Meta, 2021). This period allows them to ask difficult questions about how the Metaverse should be built, for instance, user accessibility. *Meta* states that:

"*We also need to involve the human rights and civil rights communities from the start to ensure these technologies are built in a way that's inclusive and empowering*." - Meta, 2021.

Summing up the importance of the Metaverse, it can be looked upon as a door that opens up for virtual reality to become a more sought-after technology. With Meta being the biggest social media platform, its focus on using virtual reality as a communication tool for work, school, and entertainment, creates a call for action regarding user accessibility for visually impaired people. Meta is more or less creating a technology that, as mentioned previously in this chapter, is heavily sight-focused, limiting its use for visually impaired people. Therefore, further research needs to be conducted to address the current problems of virtual reality for visually impaired people. Thus, identifying the current limitations and creating a more accessible environment for the visually impaired when Metaverse potentially becomes the leading technology to use among the public.

2.6 Current Problems for Visually Impaired Users in Virtual Reality

2.6.1 Introduction

This section will present the current problems, and limitations visually impaired people interact with while using virtual reality. It is critical to identify the problems and address them with a possible solution to create a more accessible and user-friendly experience. The literature in this section will also form the basis of the data collection chapter, introduced after this chapter.

The use of technologies has seen significant growth in the last decade. Virtual reality introduces a new and exciting way to experience computing, creating an immersive and intuitive way of interacting with the latest virtual worlds. As mentioned in this paper, virtual reality's hallmark is the head-mounted display entirely reliant on the user's sight and visual field. The head-mounted displays work for people with functioning vision; however, sight reliant head-mounted displays are not a well-functioning technology for users with vision impairments, resulting in the additional need for user accessibility features to stay attainable. According to The World Health Organization, it is estimated that 2.2 billion people have some level of vision impairment (WHO, 2021)**,** with around 237 million of these people being further categorized as severely impaired (Adelson et al. 2020).

Therefore, lack of user accessibility is a problem in virtual reality and the world. A 2022 study done by the *United Nations*, *Department of Economics and Social Affairs Disability* estimates that in the United Kingdom alone; "*75 per cent of the companies of the FTSE 100 Index on the London Stock Exchange do not meet basic levels of web accessibility, thus missing out on more than $147 million in revenue."* (Un.org, 2022). Furthermore, *World Health Organization (WHO)* states that vision impairment poses an enormous global financial burden, with the "*annual global costs of productivity losses associated with vision impairment from uncorrected myopia and presbyopia alone estimated to be US$ 244 billion and US$ 25.4 billion, respectively."* (WHO, 2021). With virtual reality gaining popularity for daily use activities, primarily through *Meta*, the number of companies that do not meet the basic levels of accessibility could be on an upward trajectory.

Money is not everything, and a more human perspective needs to be addressed to showcase the importance of creating virtual reality as problem-free as possible. As showcased earlier in this chapter, virtual reality is no longer only used for video games but also in other areas that could create a particular interest for people with visual impairment. People with visual impairment can use virtual reality to perform specific tasks or learn certain actions that can be hard in real life, such as crossing a road. Rehabilitation techniques can also be used for newly visually impaired users who are not born with a visual impairment but get their vision impaired later in life. In addition, with the growth in virtual reality, new applications are being created, resulting in new opportunities for visually impaired users to minimize the effects of visual impairment and enhance their social participation, resulting in a better quality of life. And not to forget the opportunity for children to provide an exciting and motivating experience, which might be limited for them in the real world due to their visual impairment. Vision impairment among children often impacts their language, emotions, and social and cognitive development, resulting in lifelong consequences. *World Health Organization (WHO)* also states that" *school-age children with vision impairment can also experience lower levels of educational achievement.*" (WHO, 2021).

Is Virtual Reality Inaccessible?

To answer this question, I will be looking at current research discussing this topic. It is essential to answer this question as it is the mainframe of the research question. In today's virtual reality development state, there are certain limitations for visually impaired users, with areas of user accessibility not being addressed enough to create a fully immersive or sustainable piece of technology for those with sight impairments. However, as previously mentioned in this chapter, it is essential to state that the degrees of vision impairment vary significantly from one individual to another. For example, one user of VR can be entirely blind, resulting in a significant amount of accessibility tools needing implementation to create a usable virtual experience for that user. On the other hand, other users might only struggle to read the smaller text and need one accessibility tool to assist them in using virtual reality. Nevertheless, these individuals are being categorized as visually impaired and need refined user accessibility tools to be addressed in a virtual reality environment.

Looking at the research done by Dr. Mar Gonzalez-Franco, a principal researcher in the extended perception interaction and cognition team at Microsoft Research, we can better understand and confirm that virtual reality does have a user accessibility problem. In her, *Does VR Have an Accessibility Problem?* Research, Gonzalez states that "*Vr has an incredible potential for accessibility because you can do things that are Impossible outside VR., But everyone can agree that VR have an accessibility problem"* (Gonzalez-Franco, 2022). Gonzalez emphasizes that virtual reality and other spatial computing technology heavily focus on digital content entering through wearable technology, like head-mounted displays or input devices. The content through wearable technology results in users with any bodily limitation having that limitation carry on to VR and, in some cases, not even being able to wear the headset (Gonzalez-Franco, 2022). Not being able to either wear or connect the VR setup, which is also problematic for some visually impaired users, will limit them from interacting with the technology altogether, resulting in technical and ethical limitations. Virtual reality is a massive leap from the current technology used by people, especially in the visually impaired community, where users interact with the content displayed on a screen, either a computer, tablet, or mobile phone. But with virtual reality, users are inside the content and interacting through their body and wearable technology, both experiencing limitations of accessible reason.

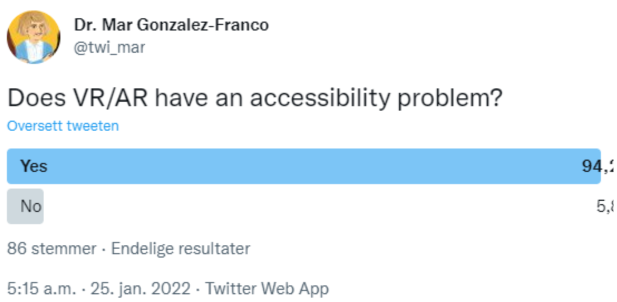


Figure 2.7 - Dr.Gonzalez's Twitter Poll (Gonzalez-Franco, 2022)

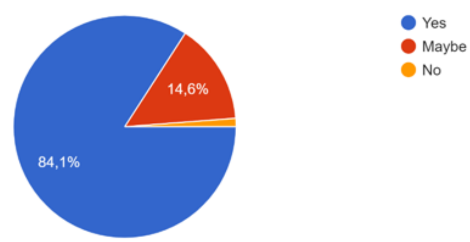


Figure 2.8 - My survey question (67 out of 82 answering "Yes") (Survey B, 2022)

Dr. Mar Gonzalez-Franco quickly underlined that virtual reality has an accessibility problem, with reasons stated later in this chapter. Dr. Mar Gonzalez-Franco also created a small Twitter poll before giving her talks. Gonzalez asked, "*Does VR/AR have an accessibility problem?*" with approximately a hundred respondents voting, resulting in 94,2% of votes confirming that VR has an accessibility problem, shown in figure 2.7. I have also created a similar poll for my survey, which will be discussed later in this thesis, giving me similar results, with 67 out of 82 visually impaired participants answering that virtual reality has an accessibility problem for them.

Visual impairment affects most virtual reality aspects, the aspects of social inclusion, use of hardware, immersion into the virtual environment, and learning, all of which can significantly affect the user's whole life, inside and outside virtual reality. Therefore, problems for visually impaired users must be identified and addressed with a solution to limit these limitations. Unfortunately, there is not one specific solution for every limitation in virtual reality, as they differ widely. However, we can address each of them individually to create a better overview.

Additionally, looking at current research and clinical trailing done on assistive technologies for visually impaired people by R. Thomas (2015), assistive technology for children and young people with low vision. Thomas is showcasing that there is still a significant lack of high-quality research on this particular subject. Thomas proves a lack of user accessibility in "*reading, educational outcomes, and quality of life for children."* Although this research was conducted in 2015 while the technology was still new, it still highlights that the accessibility technology did not get enough recognition when creating the new era of virtual reality, and much has not changed since then. Therefore, we can still value Thomas's research to underline that visual aids and user accessibility have a gap in clinical research. To further support this statement, we can look at Deemer's et al. (2018) study on *Low vision enhancement with head-mounted video display systems: are we there yet?* Where Deemer studied the enhancement of head-mounted displays for low vision users. By the conclusion of his study, Deemer suggested that many limitations have been addressed and resolved even after 20 years since the first concept of virtual reality was introduced. Nevertheless, there are still many limitations in the current virtual reality for low-vision users, and more research on this topic is needed (Deemer et al., 2018).

2.6.3 Color Blindness

In this section, I will be presenting one of the most common forms of visual impairment, color blindness. According to Clinton Eye Associates, color blindness affects approximately 300 million people worldwide (Clintoneye, 2022). This condition is one of the few addressed in some virtual scenarios. I will showcase the solution created for color blindness in this section presented with one example; however, further discussion of color blindness will be presented in chapters five and six, which will show the data gathered from the survey about color blindness and a possible solution for addressing this problem.

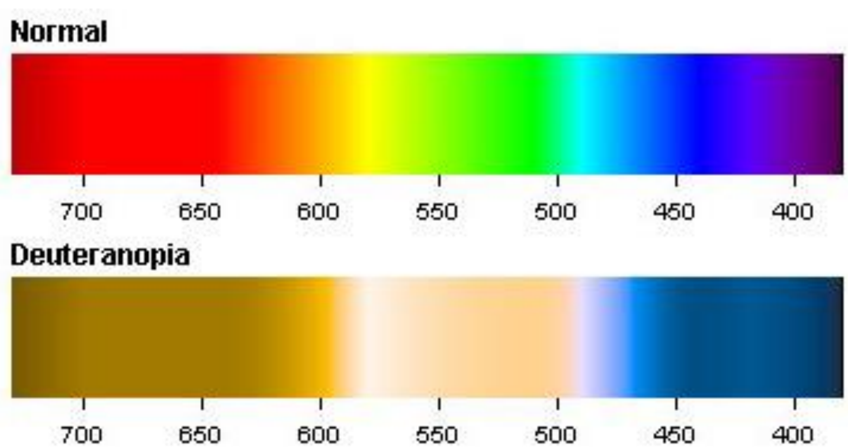
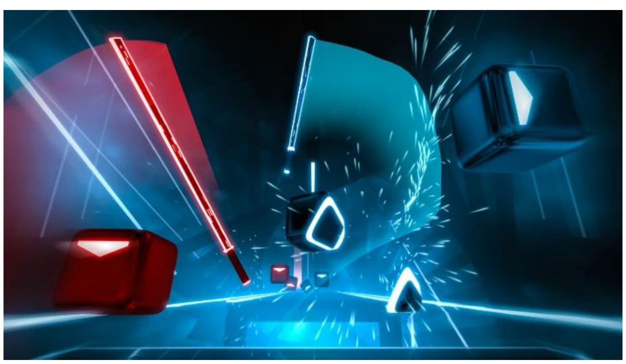


Figure 2.9 - Color Perception (Colblindor, 2022)

Normal trichromatic color vision is based on three different types of pigments in the tapping cells (S-, M-, and L-tapping). The sensitivity curves of the pin pigments overlap, and the different reaction of the pins to different wavelengths gives us trichromatic color vision (Krekling, E. D., Hagen, L. A. and Baraas, R. C.2018). When a specific tapping cell is missing, different color receptions are representative of a person, creating color blindness. Mari Kyle, a content launch manager for Facebook Reality Labs, describes the most challenging color perceptions to be *protanopia, tritanopia,* and *achromatopsia.*

Protanopia accrues when the L-tapping is entirely missing, making the person unable to perceive the colors red and green, which is essential for virtual reality if we look at the *color theory* (Color, 2022). It is a theory that colors are designed to indicate specific actions, in which the color **red** often indicates the action to stop or danger. In contrast, the color **green** indicates the action to "go" or has a meaning of "safe," a theory essential for virtual reality as video games often use it to display information and directions. Similar indications can be found in real life, with traffic lights indicating the same information. **Tritanopia** is color blindness, where a person cannot distinguish between blue and yellow colors. **Achromatopsia** is color blindness, where the person cannot see any colors, just shades of white, grey, and black.



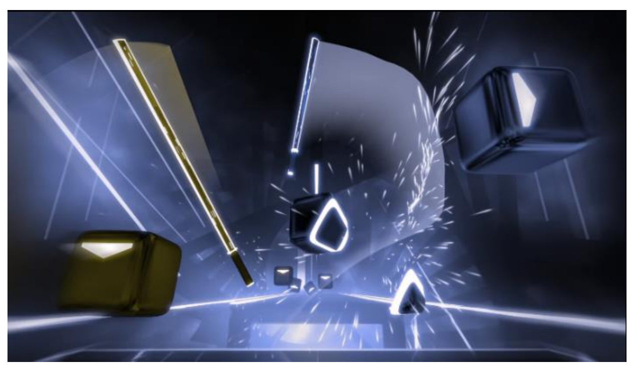


Figure 2.10 - Beat Saber without color blindness (Beat Saber, 2019) **Figure 2.11** - Beat Sabe seen with protanopia (Beat Saber, 2019)

To see how these limitations can be addressed, I have chosen the popular virtual reality game *Beat Saber*, a "*VR rhythm game where you slash the beats of adrenaline-pumping music as they fly towards you, surrounded by a futuristic world*" (Beat Saber, 2019). This VRs game's main objective is to hit incoming colored squares with a matching color of the saber. As a default setting, the squares and sabers are colored red and blue, where the player's objective is to hit the red squares with the red saber to collect points. To showcase the limitations some color-blind users, experience while playing Beat Saber, this paper showcases screenshots of the game and inverted the colors to match the different color perceptions.

Figure 2.10 displays Beat Saber's normal color perception, equivalent to how a non-color blind person perceives the colors. *Figure 2.11* displays how players with protanopia perceive Beat Saber, with color blindness limiting the red and green colors. Players can still perceive a difference between the original red and blue square. However, the optimal recognition of correct colored objects is not optimal, as the square is displayed in a faded yellow color, creating limitations. "Viewing objects in the distance" is also a limitation in virtual reality due to vision impairment, as color blindness creates a significant restriction in distance viewing. With protanopia, it is significantly harder to identify the color of the incoming square in figure 3.11, creating a problem as *Beat Saber* is a game requiring fast reaction times from the player. The red & blue-colored squares can shift sides, resulting in the player with protanopia having little to no reaction time, giving a limiting and less motivating experience. Being able to view objects at a distance is crucial for the player's experience. In addition, the contrast between the background and blue squares is also challenging to identify.

How can Color Blindness be Addressed?

The accessibility problem for colorblind users was addressed by the creators of *Beat Saber* in early 2020, making the game far more accessible for players by giving them the option of changing the colors of squares, sabers, and backgrounds according to their preference.
Figure 2.12 shows the ability to select pre-build options for the player; this is another form of accessibility where developers create a range of pre-build settings for players to choose from without having to create everything themselves, an action which can also be limiting for some. However, if players choose so, they can select colors of their liking, as shown in *figure 2.12*. The pre-built options allow the player to select their preferred colors, showcasing that every disability is different in its own way and that user accessibility options are essential. Color blindness can vary substantially from person to person. Not every pre-build setting by the developers will fit everyone; therefore, giving the player an option to select their colors makes the game even more accessible.

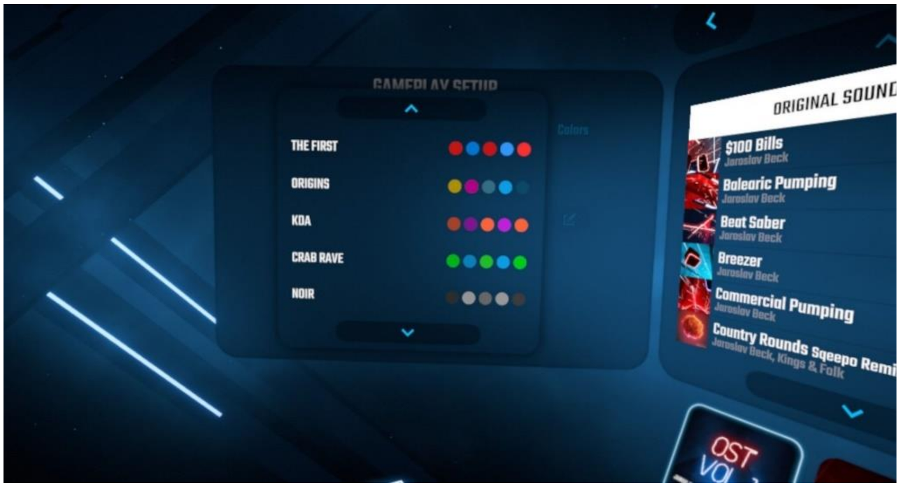


Figure 2.12 - Pre-build options of colors for the player to choose from (Beat Saber, 2020)

The ability to select different colors in the game gives a perfect example of user accessibility; this was previously mentioned in this chapter. In which the chapter introduced the *inclusive design*, which means that the option of changing color is not only for user accessibility point of view for color-blind players but also for everyone else who perhaps prefers different colors. Either from the aspect of usability or simply because they want to use their favorite colors.

What about users with achromatopsia?

Players without any color perception will find a range of games challenging to interact with, with *Beat Saber* being one of them as it is heavily focused on color perception. Figure 2.13 shows how a player with achromatopsia perceives *Beat Saber*, with the condition limiting the experience down to almost unplayable.

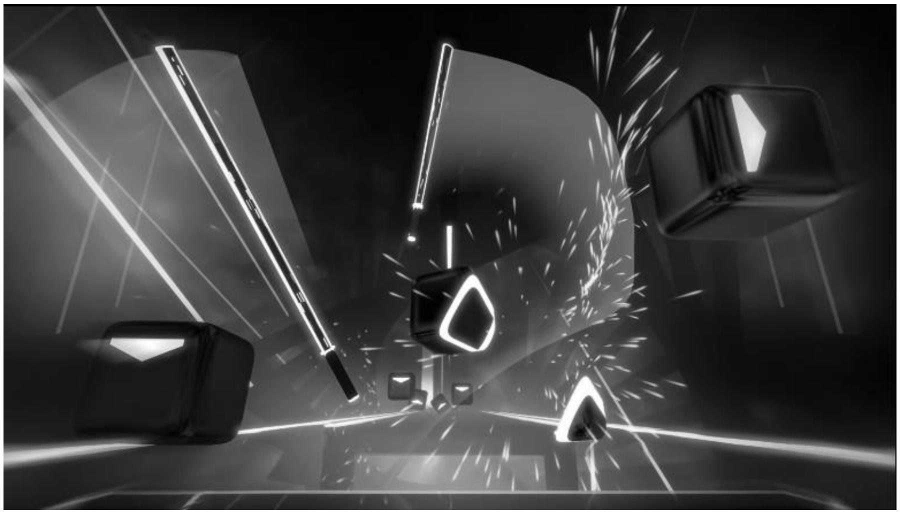


Figure 2.13 - The smaller triangles on top of the squares only indicate which side to hit the square from, not their original colors. (Beat Saber, 2019)

To solve the limitations of only perceiving black and white tones, we can look at the *theory of design* by Rebecca Hagen and Kim Golombisky in their book *White Space is Not Your Enemy*. They describe the design theory, precisely the aspect of shapes and forms. First, inorganic shapes and forms such as perfect circles and squares can be easier to identify (Hagen, Golombisky, 2017) – something that *Beat Saber* already takes to use. Furthermore, "*shapes can trigger instant recognition"* (Hagen, Golombisky, 2017), something which is not used frequently in *Beat Saber* but often can be experienced in the real world without us even thinking about it, such as triangles with the use of exclamation marks inside them to display danger/ need of caution. To make *Beat Saber* more accessible for achromatopsia players, the developers could incorporate different shape designs to make recognition of difference more accessible. Instead of relying on colors, shapes could be used to do the same task. This option is not only a solution for *Beat Saber* but a solution for user accessibility in many virtual reality fields.

Color blindness is the most popular type of visual impairment, showcases that possible accessibility options are likely to develop within the virtual application, such as seen in the Beat Saber's settings menu. To further support the theory that color blindness is a common type of visual impairment, a survey will be presented in chapter five, where numerous participants experience color blindness, collecting data about the limitations following that visual impairment. Finally, chapter six will present the *SeeingVR* toolkit study created by Dr. Zhao (Zhao, 2019), which will present a solution to make virtual reality more accessible for color blind people using the *SeeingVR* toolkit.

2.6.4 Interface

This section will present the limitations in interfaces in current virtual reality for visually impaired users. Examining existing literature and my survey indicates that one of the main problems for visually impaired users is seeing and using the interface. These interfaces, either the menu or a pop-up message in the game, are often difficult for the visually impaired to read as the font size is small with no accessibility tools to enlarge the picture. In computer and mobile design, there are several ways to better the accessibility for the visually impaired. With software providing magnifying or adjusting the size of the text or browser, these software tools are limited in virtual reality, making it hard or even impossible for many users to read or interact with the text displayed.

Virtual reality is still a relatively new type of technology, with a less developed quality of screen than computers, resulting in disapplying worse quality content and perhaps creating an additional need for accessibility tools.

> "*something that was accessible for a visually impaired user on a computer might become less accessible in VR*" (Mari Kyle, 2020).

Therefore, it is crucial to develop accessibility tools that can aid visually impaired users in interacting with smaller text and interfaces. Unfortunately, looking at Tyriel Wood's "Oculus Quest 2 Software Tour" (Wood, 2020) as an example, it is reasonably easy to see that interfaces in Oculus Quest 2 do not fulfill all user-accessible requirements to create an accessible interface for visually impaired users.

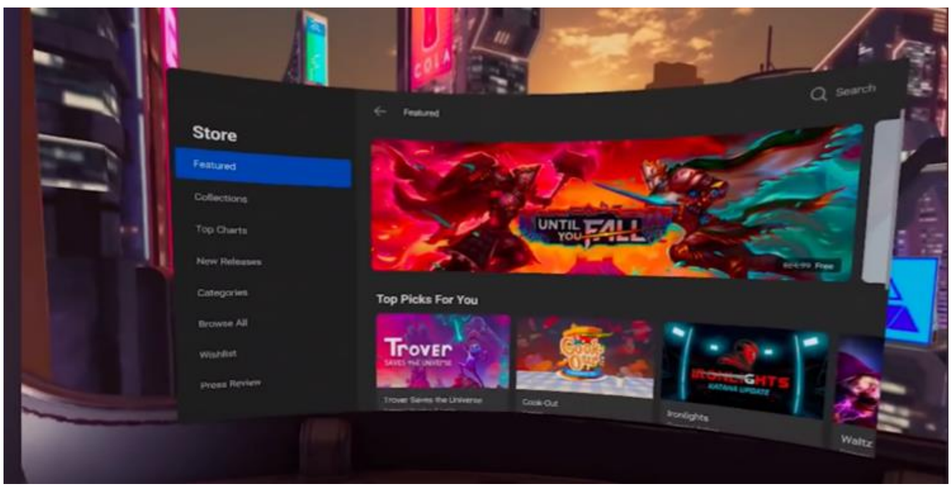


Figure 2.14 - Oculus Rift Store Interface and Background (Wood, 2020)

Rebecca Hagen and Kim Golombisky, in their book *White Space is Not Your Enemy,* discuss the importance of proper design for visibility & readability, emphasizing that these two are critical for users. Readability means readers can easily read it; visibility means viewers can see it clearly, which is highly important for visually impaired users. Contrast can resolve these problems (Hagen, Golombisky, 2017). Looking at figures 2.14 and 2.15, one can see that the contrast between the background and the primary interface for the user is hard to distinguish, making it hard for the visually impaired to interact with it. In addition, the font size is extremely small in comprising what could be achieved with an accessibility tool or a larger interface screen/text.

Figure 2.15 - Oculus Rift Review Interface (Wood, 2020)

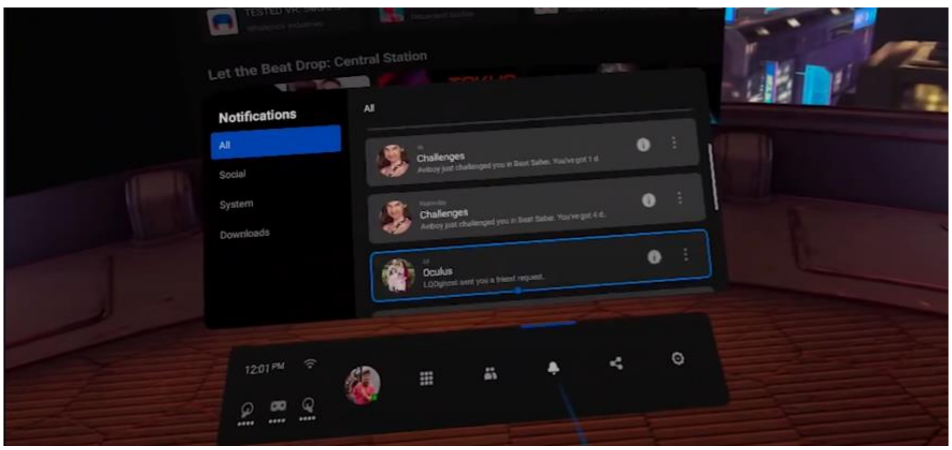


Figure 2.16 - Oculus Rift Notifications (Wood, 2020)

Figure 2.16 is another example of how inaccessible the content is to read for visually impaired users, with the notification bar, text, and interactive buttons being small in size. Unfortunately, this trend is repeating in virtual reality design. Virtual reality emphasizes the feeling of immersion over accessibility, with smaller interface screens and extensive open backgrounds and surroundings to create the feeling of being in a virtual world, which results in a less accessible world for the visually impaired.

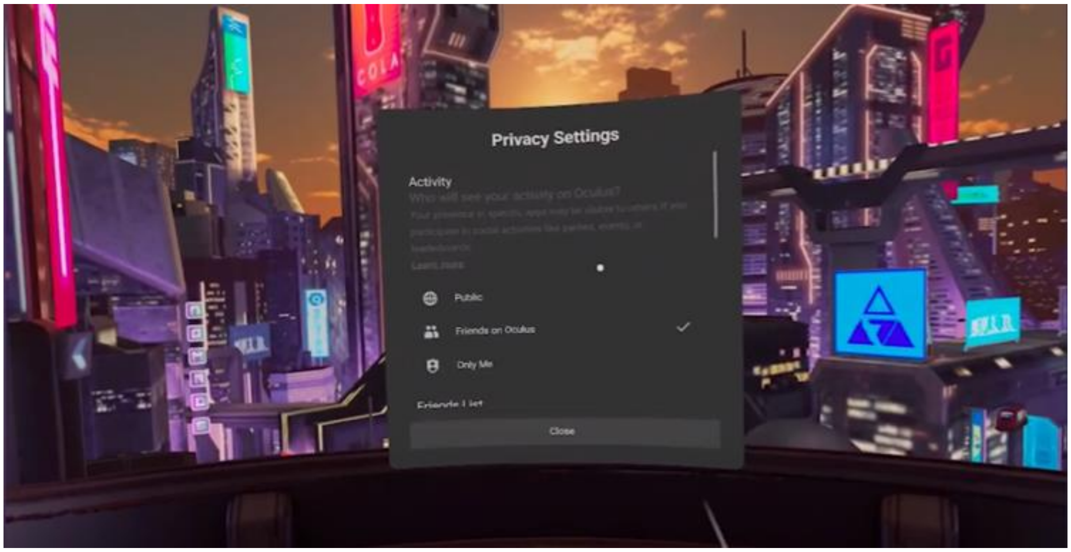


Figure 2.17 - Oculus rift Privacy Settings (Wood, 2020)

As Hagen and Golombisky mentioned, the contrast makes design elements look different and convey the information by making the element stand out (Hagen, Golombisky, 2017). For example, in *figure 2.17*, information for privacy settings, essential for many users, is displayed with grey text and a grey background. That combination of colors results in a significant lack of contrast, making it even hard for a non-visually impaired person to read, then even more so for someone who is visually impaired.

How can the Interface Problem be Addressed?

To address this problem, not only in Oculus Quest 2 but in every game and virtual reality interface, a user accessibility tool for zoom-in, text enlargement, or especially screen readers for fully blind users need to be implemented to make virtual reality user-accessible. In the next chapter of this paper, we will be looking at *SeeingVR*, a user accessibility tool developed to create a more user-accessible virtual reality.

An important point to address is the possibility of using motion tracking to benefit the zoom-in effect. While perhaps not having a zoom-in software implicated in virtual reality, the ability to physically move the head in real life to convey that movement into virtual reality is a possibility, as mentioned by multiple people in my survey. However, while this ability makes it possible for a user of VR to move their head closer to the displayed text or interface, some limitations are also created for that specific task. *Jesse Anderson*, a legally blind user I interviewed, states that these interfaces are not always compatible with motion tracking (Anderson, 2022). While users can move their heads closer to the interface, the interface relocates further away from the user. They indicate that some interfaces have an invisible barrier that keeps relocating the interface away as the user reaches the limit. If the invisible barrier is not integrated, then the feature of motion tracking and physical movement can work to enlarge the interface. However, the essence of user accessibility tools is overweighing the ability to move the head closer, as physical movement is not possible for everyone, with users having movement limitations and not being able to perform the task of moving their heads. As previously mentioned, an *inclusive design* choice where a user accessibility tool could assist visually impaired users and those who have different limitations.

To further support the problem of interface inaccessibility, I collected data about the interactions with interfaces through an interview and survey in chapter five. To address this problem and look at previous solutions, I will be looking at Zhao's *SeeingVR* toolkit in chapter six (Zhao, 2019), which creates various tools to make interfaces in virtual reality more accessible.

2.6.5 Haptic Feedback

In this section, I will be presenting the problem with haptic feedback for visually impaired people. As previously mentioned, haptic feedback is often one of the senses that visually impaired people can carry over from the real world into the virtual world without learning how to interact with it. An example of this will be showcased later when discussing the *Canetroller* (Zhao, 2018), where fully blind people can convey their haptic feedback by using a white cane in real life over to the *Canetroller*. Therefore, haptic feedback is essential to address and include in virtual reality development.

As mentioned earlier, haptic feedback is the sense of touch that communicates the information to the user, a "sense that emerges when [a body]'s properties are processed as if they were the properties of one's own biological body" (Kilteni et al., 2012). In virtual reality, haptic feedback is mainly experienced through the input devices like the controllers, giving a range of vibrations when an action is performed inside the virtual reality. An example of this is the previously mentioned game *Beat Saber*, where a slight vibration occurs when the players successfully hit the incoming squares. Haptic feedback is mainly used to communicate information that gives the user the indication of what is happening, something visually impaired people in real life commonly use. For example, *the Lighthouse for the Blind, Inc.* describes the use of a white cane by visually impaired and blind people as being a vital mobility tool to navigate the world safely and independently (lhblind, 2021). A white cane indicates the surface and possible obstacles in front of the visually impaired person using it. Furthermore, the texture of the ground is communicated to the person through haptic feedback – vibrations traveling through the cane up into the hand. Thus proving that haptic feedback is an essential sense for visually impaired people and implying it in virtual reality could result in improvement.

The problem with haptic feedback in virtual reality for visually impaired people is the small amount of haptic feedback being transferred and integrated into the software of games or other media used in virtual reality. Furthermore, if haptic feedback is being used, it often has superficial feedback which is not precise enough to indicate specific details, which would have been helpful for visually impaired users. Haptic feedback is needed as an aspect of user accessibility to indicate when they have picked up an object, or a menu has been selected. The fundamental haptic vibration can achieve this; however, indicating what the object being held is or its shape is currently a limitation for visually impaired people as it is impossible. Thus further development of haptic feedback needs to be implicated.

Chapter six will present the development of a *canetroller* as a problem solution to the lack of haptic feedback, where a haptic feedback coil was developed to provide feedback on different textures of the ground. The study conducted on multiple fully blind participants by Dr.Zhao was proven useful. (Zhao, 2018).

2.6.6 E-learning & Social Precipitation Problem

In this last section of this chapter, I will present the problems with e-learning and social precipitation, as these two are crucial aspects of virtual reality, especially with the focus on the Metaverse which plans to sginificantly focus on these areas. The previously mentioned aspects of virtual reality and their problem can be tied into this section, as problems with interface aspects will affect e-learning and social precipitation.

The absence of significant accessibility tools development in virtual reality can create a methodological issue for visually impaired users: content interaction. As mentioned earlier in this chapter, the content interaction can be in a video game interface, but even more importantly, it can be in an educational context. With a vision impairment or complete loss of vision, students must rely on input from their physical senses, such as touch or hearing; however, most e-learning environments assume the learner has a functioning sight, creating limitations for the visually impaired. (Harper, S., Goble, C., Stevens, 2001). Peter Fenrich describes how multi-media sources can be accessed through many different ways of delivery; "*Considering e-learning, simulations, active experimentation, discovery-learning techniques, questioning with feedback, video, animations, photographs, and practical hands-on skills, can be utilized for virtual teaching"* (Fenrich, P. 2005). These multi-media sources and other tools in virtual reality may meet the technical accessibility requirements yet be significantly inaccessible for a blind student because it is designed with a visual interface in mind (Harper, S., Goble, C., Stevens, 2001). As a result of inaccessible content, students with severe vision impairment will not have equal opportunity to gain tertiary qualifications or skills because of their disability and lack of user-accessible tools created to help them precipitate in class.

E-learning & social precipitation is becoming a more prominent problem as Meta is trying to incorporate virtual classes, work meetings, and social gatherings into their future use. It will be inaccessible from the technological point of view and from a social aspect where the majority of people might end up using virtual reality daily. Inaccessible virtual reality will lead to participation restrictions on the environmental factors for visually impaired people, with exclusion from social networks and independence through personal access to information (Gerber, 2003).

With the growth of virtual reality, the importance of e-learning is growing as a possible solution for visually impaired people, especially fully blind users, to use this technology as a learning and rehabilitation tool. A further example of this will be presented later in this chapter, such as *Canetroller* by Zhao et al. (2019). Further supporting this statement, a newer study by Calabrese states that VR accessibility and the possibility for virtual reality to be used for rehabilitation services via head-mounted display systems remains *in its infancy, and effective design remains an open challenge* (Calabrese et al., 2021).

2.7 Summary of Chapter Two

This chapter introduces and establishes critical factors of this thesis, such as visual impairment, virtual reality, and user accessibility. By using a range of academic literature, I show the importance of why the topic of accessibility for visually impaired users of virtual reality needs to be further addressed. I introduce Meta and the concept of *Metaverse*, which is one of the main factors for the rise in popularity of virtual reality devices. To further address the accessibility problem for visually impaired people, I present the problems and limitations often experienced by visually impaired people. Identifying the problems allows me to, later on in this thesis, provide possible solutions addressing the specific problems. However, to further support the current problems visually impaired users experience, more data needs to be collected to support the literature presented in this chapter. In the upcoming chapter, I will present the methods I used to collect the data to further support the problem section.

CHAPTER THREE: METHOD AND MATERIALS

To answer my research question and support my main point that virtual reality has a user accessibility problem and requires further addressing to include visually impaired people, I will collect data to support the research problem. To showcase how and why the data have been collected, I will use this chapter to describe the research design of my project and discuss the rationale of the methods and materials chosen to investigate the research problem. For my research, I decided to use a mixed-methods approach. Therefore, I conducted quantitative and qualitative methods to obtain a more detailed description of reflections from interviewing specifically selected participants, which led me to narrow the general data using an online questionnaire. Furthermore, in this chapter, I will describe both quantitative and qualitative research methods and discuss the chosen material and design process of the data collection procedures and the context of the study. After that, a description of chosen participants, the criteria behind choosing the selected ones, and how the data gathered from them were analyzed—followed up with the reliability and importance of ethics when carrying out my research project. To describe the research methods and guide me through data collection, I will mainly follow two books; John W. Creswell's 2012, *Educational Research: Planning, Conducting and Evaluating Quantitative and Qualitative Research – 4th ed.* And John W. Creswell's 2014, *Research Design: Qualitative, Quantitative And Mixed Methods Approaches - 5th ed.* As I found Creswell's books to be the best academic source to guide my methodology and help me conduct, read, and evaluate my research studies. Creswell is a well-known author in the academic field of mixed methods, with numerous articles and books on research design, qualitative research, and mixed methods research (Creswell, 2022).

3.1 Qualitative and Quantitative Research Methods

In this section, I will be presenting both qualitative and quantitative research methods. According to Creswell, the majority of methods to collect data in academic research happen either through qualitative or quantitative methods, each of them being different from one other. Therefore, it is essential to distinguish the difference between these two methods and define them. In this part of the chapter, I will explain qualitative and quantitative methods according to Creswell's *Educational Research* and *Research Design*, describing why these methods were chosen to conduct my research for this paper.

Creswell describes **qualitative** research as a type of research where a problem is explored by developing a detailed understanding of a central phenomenon. The qualitative method usually collects information based on information from a small number of participants, obtaining their personal views (Creswell, p. 16, 2012). Qualitative methods can collect information through interviews, field notes, and observations. For this project, I chose to conduct interviews as my qualitative method and include qualitative questions in the online questionnaire – survey A. By conducting the qualitative approach, I managed to follow Creswell's way of exploring the problem by interviewing and getting a deeper understanding of a phenomenon when investigating the participants' thoughts on the topic. As proven later in this paper, through interviews, I managed to gain a more personal and in-depth opinion of virtual reality by visually impaired individuals. However, this method does result in significantly fewer responses as interviews do take more time. To resolve the problem of few answers, one can apply the quantitative approach to collect a more considerable amount of data but with fewer details.

Creswell describes **quantitative** research as "identifying a research problem based on trends in the field or on the need to explain why something occurs. Describing a trend means that the research problem can be answered best by a study where the overall tendency of responses from individuals varies among people" (Creswell, p. 13, 2012). Thus, quantitative methods can collect a considerable amount of data with variants of answers. Furthermore, a quantitative survey or questionnaire has the ability to reach a more significant number of informants if distributed and shared via a link on the internet, a method I used twice in my research to gain the best possible data for my research. Therefore, the quantitative research method is the primary method used in this paper. However, since I conducted both qualitative and quantitative methods, it becomes, according to Creswell, a "mixed methods" research method.

Mixed methods

I chose the mixed methods design for my research, which "involves combining or integrating *qualitative and quantitative research and data in a research study*" (Creswell, 2014, p. 14). Creswell describes the value of using the mixed methods in research as "*residing from the idea that all methods had bias and weaknesses, and the collection of both quantitative and qualitative data neutralized the weaknesses of each form of data*" (Creswell, 2014, p. 14-15). Using mixed methods, I collected data that presented meaningful solutions for my research, both through qualitative interviews and quantitative surveys. By doing so, I managed to neutralize the weaknesses of each form of data, resulting in what I felt was an overall better result for my research problem. To further support the choice of this method, I will be presenting in detail each choice behind choosing both qualitative and quantitative methods for collecting my data later on in this chapter.

According to Creswell, there are multiple types of mixed methods design, as the sequence of performing individual methods has a different outcome of collecting the data. I chose to use what Carwell defines as the exploratory sequential design for my research. I first started by collecting *qualitative data,* and then, based on the results gathered from the *qualitative data*, I collected the quantitative information. The purpose of conducting my mixed methods in an *exploratory sequential mixed methods design* is to, according to Carswell, “involve the procedure of first gathering qualitative data to explore a phenomenon, and then collecting quantitative data to explain relationships found in the qualitative data.” (Creswell, p. 543, 2012). The overall reasoning behind this chosen method was generated by a lack of known or available research for the population on the specific topic (user accessibility for virtual reality, and especially in a particular group of users (visually impaired people). This method helped me gather data for my research by using different methods to build further possibilities and collect more data.

3.2 Research Question

My goal is to gain insight into and develop an understanding of how the lack of user accessibility in virtual reality impacts visually impaired people. An overall aim is an increased understanding of virtual reality, and its user accessibility features and tools to improve the usability for visually impaired people. To further support this aim, I will showcase that virtual reality does have user accessibility problems. The lack of user accessibility and its problems lead to visually impaired people not being able to successfully use the technology, as it is mainly designed for non-visually impaired users. In addition, I am hoping to underline the importance of current research developed toward creating a more accessible virtual reality. Further focusing on importance, I aim to showcase the difference between low-vision and blind users. The differences in user accessibility need to be addressed for each group to successfully limit the majority of user accessibility problems the visually impaired community faces while using virtual reality.

To gain an understanding of how the lack of user accessibility in virtual reality impacts visually impaired people, I need to identify what works and what the main problems and limitations for visually impaired people are.

3.3 Research Design

To showcase the reasoning for my methods while collecting the data to answer my research problem, I will describe my research design in this part of the chapter. By doing so, I will explain my reasoning for choosing an exploratory sequential design and how I went on to implement it into my research. In addition, I will be presenting my methods for initiating contact with selected groups and individuals suitable for my study, each approach for collecting data through interviews and surveys, and discussing limitations I stumbled upon while collecting the data and how they affected the outcome. Finally, this research design will be presented in chronological order, supporting the exploratory sequential design.

3.3.1 Approach to Collecting the Data

To answer my research problem of how to create a more accessible virtual reality for visually impaired people, I wanted firstly to get in touch with the visually impaired people who, preferably, had some prior experience with VR. By collecting data from this specific group of "visually impaired people who have tried virtual reality," my data collection would become more accurate for my study. However, as this paper showcases, virtual reality can be inaccessible for visually impaired people, often categorized as technology for entertainment rather than something useful for visually impaired people, such as computers or phones. Nevertheless, with the growth of virtual reality in popularity in past years, I hoped that enough individuals have tried using VR at least once, enabling me to collect valuable data. However, as I will showcase later, an option for "never tried" was included in each of my surveys, as information from a visually impaired individual could still be proven valuable to my research.

As my knowledge of visually impaired people or groups was minimal prior to writing this thesis, I had to seek contact and information through groups and social media. Firstly, I contacted *The Norwegian Association of the Blind for the Visually Impaired* "Norges Blindeforbun Synshemmedes organisasjon" (Blindeforbundet, 2022). The association is divided into Norwegian counties, meaning each county has its contact information I could contact them through. As a result, I sent out eleven e-mails to each county containing the same content. In the mail, I introduced myself, presented my research, and asked if there any people would be interested in answering my question through an interview or a group interested in answering my surveys. From those eleven e-mails, I received three responses: two directing me further to individuals fitting my criteria and willing to participate in my interview, and one response leading me further to a Norwegian IT-focused group for visually impaired people on Facebook named “Synshemmedes IKT-nettverk” *Visually impaired ICT networks*, with around 1 200 group members.

In addition to contacting *The Norwegian Association of the Blind for the Visually Impaired*, I used XR Access, a virtual reality community for people with disabilities, where I came in touch with predicaments willing to answer my questions (XR Access, 2022). Lastly, I also used Reddit/blind, a social community for the visually impaired people with 16.000 users at the time of my research (R/Blind, 2022). Not every group participated in both of my research methods. Therefore, I will mention them individually when describing each method in the upcoming subchapters. By finding the groups and individuals fitting my description of criteria of a visually impaired person who has used virtual reality, I was ready to start conducting my study.

3.3.2 Why Exploratory Sequential Design?

I decided to follow the exploratory sequential design based on my prior knowledge and research found on my topic. However, virtual reality is quite a new medium; thus, further narrowing it down to a group of visually impaired people resulted in me researching a topic with little prior research–hence why I am writing this thesis. Furthermore, I firmly wanted to talk with someone who was visually blind and has used virtual reality to gain a better understanding of their personal experiences. To do that, I started with interviews, where I interviewed individuals about their experiences. By doing so, I could better understand how they experience virtual reality, which further supported my creation of online surveys. The surveys were my primary method of gathering data to support and answer my research question.

By following the exploratory sequential design, I was first able to conduct *qualitative* data collection and analysis. The results of qualitative data helped me better understand the overall experience of virtual reality for visually impaired people, therefore building to a better *quantitative* data collection and analysis done by surveys. The result of quantitative surveys further helped me interpret the results of my comprehensive study, providing me with an answer to my thesis research question.

Exploratory Sequential Design, which I used to collect my data, looks as follows: (Creswell, p. 541, 2012)

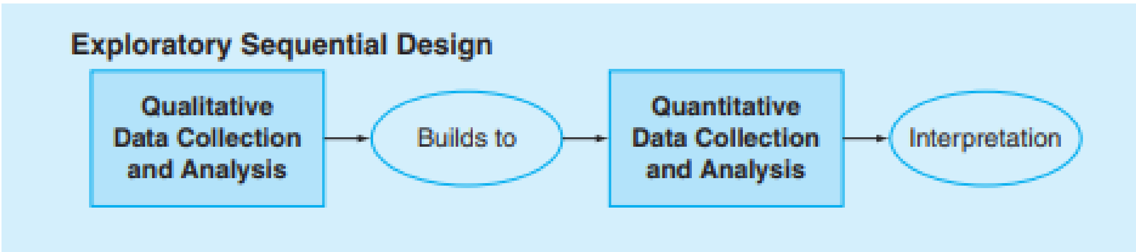


Figure 3.1 - Exploratory Sequential Design (Creswell, p. 541, 2012)

3.4 Data Collection Introduction

As mentioned previously in this chapter, I decided to conduct an exploratory sequential design for my study, meaning I opted for using interviews and surveys to collect my data for what I meant was the best possible result. In this part of the chapter, I present thoughts and choices behind the planning of the interviews and surveys. In addition, I will introduce what research interviews and surveys are and their different approaches to carrying them out. Finally, I will discuss the advantages and disadvantages of carrying out these two methods and what limitations accrued for me specifically while carrying them out.

3.5 Interviews

In this section, I will present and discuss how I went on to interview three visually impaired people who have experience with virtual reality use. I will also present which choices I have made to gather data in a way that will further help me construct the surveys. In addition, I will also introduce the methods I have chosen to create the interviews, how I selected the informants, and introduce the design of the interview guide.

A research interview is a conversation between the researcher and an informant, which can be used to understand the chosen research topic better. Creswell defines interviews as "when researchers ask one or more participants general, open-ended questions and record their answers" (2014, p. 6). In addition, Creswell mentions that interviews can be conducted in either focus group interviews or one-on-one interviews (2012, p 218).

I chose the one-on-one interview for my study because a group of visually impaired people can have significant disability differences from one another, as I have showcased throughout my paper. I will further support this statement by showcasing the data collected in the next chapter. Another factor that made me choose the one-on-one interview was the amount of detail one can collect from a one-on-one interview. Compared to a focus group, each individual would have less time to answer and potentially not describe their experience with virtual reality in detail. Other factors which kept me from conducting the group interviews were also deciding on my approach. Pitfalls, a situation where someone talks more than others, could occur, and the participants could steer each other's thinking directions, resulting in biased data. The COVID-19 pandemic also played a role in choosing an interview method, where social gatherings were prohibited, resulting in me having to conduct the interview through *Zoom* or another form of videotelephony. Communicating through a computer already proves to be less personal without the face-to-face human interaction, and doing a group call where participants might be sitting for minutes without the ability to talk was something I did not find fitting for my study. However, the most significant factor for choosing the one-on-one interview was the disability differences each visually impaired individual could hold; it was essential for me to better understand their disability, which a one-on-one interview could provide.

For my data collection method in interviews, I chose to use the semi-structured method as it allowed me to improvise follow-up questions based on the participant's responses (Rubin & Rubin, 2005). By using the semi-structured method, I was able to follow my pre-made interview guide, with the ability to create follow-up questions. This method was proven helpful when one of my interviewees did not have as much virtual reality experience as I initially thought. Nevertheless, I managed to gather helpful information for my research by using the semi-structured method and improvising several questions based on the participant's answers.

Based on multiple factors contributing to this choice, I decided to perform the interviews through Zoom. Firstly, as I mentioned earlier in this chapter, the COVID-19 pandemic limited my ability to meet individuals. Usually, I prefer an in-person interview, as it grants a more personal feeling. However, while the pandemic limited me from meeting people in person, it forced me to search for participants outside of Bergen, Norway, where I am located, opening up more possibilities to get in touch with a more significant number of people. This initially resulted in me conducting interviews with participants from Oslo, Sweden, and the US. Even if I would have found participants located in Bergen, the use of *Zoom* creates a more accessible opportunity for connection with visually impaired participants rather than proposing to meet in a public place. Furthermore, I deliberately chose *Zoom* as the platform for my interviews based on several factors prior to my knowledge. Firstly, I knew that my interviews were conducted with individuals who experience sight impairments, meaning that sound quality is of more excellent value than the quality from my web camera. Therefore, Zoom was my preferred option based on the sound quality and sheer availability acquired by the majority of the population during the pandemic (vox, 2020). However, if the participant would comment on their preferred choice of interviewing with fit them better, I would opt for that alteration instead of *Zoom*.

For the language of interviews, I firstly created two outlines with related questions, one in Norwegian and one in English. The reasoning behind this choice was my planning to conduct interviews outside of Norway, therefore opting for an English version. On the other hand, I still created a Norwegian version for the informants based in Norway; even though I believe the English version could also work, I wanted my informants to feel comfortable expressing everything, minimalizing any data being excluded as a consequence of possible language barrier.

3.5.1 Selecting Participants – Interviews

The interviews were conducted at the beginning of 2022, and in this section, I will present my choices and thoughts behind selecting the participants.

Cresswell states that it is essential to identify participants' characteristics (Creswell, 2014, p. 230). For my study, the characteristics of the participants I chose to interview were set to contain two specific criteria. Firstly, I sought out visually impaired participants, as this is my focus group for the whole thesis. However, based on my previous research done before conducting the interviews, visual impairment has many different levels and types of affecting the vision, which means that interviewing individuals with every kind of visual impairment would be nearly impossible or could take tremendous amounts of time. As a result, I decided to interview at least one individual from each visually impaired "groups." The groups, as previously mentioned, are between low-vision people, who can still use a percentage of their vision to navigate the environment, but often need some assisting tools. Moreover, the other group contains people who identify as fully blind. By interviewing at least one individual from each of these groups, I would better understand the needs and experiences of each of them experience. It is important to remember that my interviews are mainly used to better understand each of these groups, as collected data would help me build up the surveys, which are my leading research for this paper. Another characteristic important to me was the prior use of virtual reality; this was proven to be a tricky criterion to accomplish. It goes against my research question where I talk about how inaccessible virtual reality is for visually impaired people – yet, I am seeking to speak with visually impaired people who have used virtual reality. Therefore, my criteria for the level at which the participants have used virtual reality before were quite open, meaning as long as the participant has used virtual reality before, it would be fulfilling my criteria. Participants with significant experience with virtual reality were preferred.

To recruit the suitable informants who fulfilled my criteria, I used both snowball sampling and purposeful sampling. Creswell describes the snowball sampling method as "a sampling procedure in which the researcher asks participants to identify other participants to become members of the sample" (Creswell, p. 146, 2012). For my study, the snowball sampling was used by contacting the previously mentioned Norges Blindeforbun Synshemmedes organisasjon" (Blindeforbundet, 2022). *The Norwegian Association of the Blind for the Visually Impaired* ". Firstly, I contacted the organization through e-mail to present myself as a master's student at the University of Bergen and then present my research. Then, after explaining my research, I asked if there were any possibilities for getting in contact with someone who would fulfill my criteria, as I was aiming for the association of the blind for the visually impaired to know someone who did. As a result, I gained four names, allowing me to conduct the interviews. However, only two further agreed to conduct the interview, in which I only ended up interviewing one out of two, as the last individual had to cancel.

As a result of only one interview gathered from the snowball sampling, I turned to purposeful sampling. Purposeful sampling is "a qualitative sampling procedure in which researchers intentionally select individuals and sites to learn or understand the central phenomenon" (Creswell, 2014, p. 10). Based on to factors, I contacted different individuals who fulfilled my criteria. Firstly, through my previous research on SeeningVR, I came across XR Access, a virtual reality community for the visually impaired, where I contacted different individuals. Secondly, I also selected one individual I came across through TikTok, where her content focused on virtual reality as a visually impaired person. For each of the individuals, I followed the same setup of contacting them through e-mail as I used for contacting *The Norwegian Association of the Blind for the Visually Impaired.* With minor alterations in content where I presented the place in which their contact information was found.

By the end of my interviews, I was able to conduct three interviews, each lasting between 25 and 40 minutes. A number of three informants is not ideal, and a more significant number would be preferred. However, since the interviews were mainly supposed to better understand how low-vision and fully blind groups of visually impaired people experienced virtual reality and be used as a guide/building block for my surveys, I found the data to provide enough data for this study. One could argue that three informants would leave me with insufficient data. However, one of my informants directed me to his YouTube channel (IllegallySighted, 2022), which provided additional content, video examples, and discussions of his experiences with virtual reality problems.

3.5.2 Interview Guide

When collecting the data, I followed a set of steps to guide my interview. Carswell explains that "The researcher selects participants and sites, gains permission to conduct the study, decides on the type of data to collect, develops means for recording information, and administers the data collection while anticipating field issues and ethical concerns" (2014, p. 255). I created a three-part interview guide for these interviews that I followed. The first part was designed to cover the formalities, such as their vision impairment, and their education and practices, allowing me to reflect on provided information for the rest of the interview. One example of this was my first informant, whose job title at the time of interviewing was "Digital Accessibility Expert," indicating that this informant may have significant knowledge in terms of the research questions presented to him. The second aimed to obtain information about their experience with virtual reality as visually impaired users. The third and last section is designed to obtain information about what the participants found limiting, the pros and cons of user accessibility in virtual reality, and possible solutions they wished to be implemented in the future development of virtual reality.

Interview guide - Introduction

This first part aims to establish the participant's background and visual impairment as critical factors for this section. This part used closed questions, with an option of further elaborating or commenting.

Interview guide – Previous experience with virtual reality

This section of the interview focused on understanding the participant's prior experiences with virtual reality. By collecting data on what the virtual reality was used for, I could correlate the use and the visual impairment the individual identified with. As a result, the collected data allowed me to create a more specific survey. As a semi-structured method for the interview, I used a combination of an open question, structured to start a conversation, rather than a simple "yes" or "no" answer. The question formulated as "how did you experience," "what do you think", and "tell me about" which I could follow up with other questions if need be. I also included closed questions when I wanted to collect specific data, such as "how much time have you spent using virtual reality?".

I also asked questions for the participants for them "to talk about" their experience with virtual reality. This open question allows the participant to interpret the question and guide it towards the experience most valuable for them, either a positive or a negative experience.

To sum up the purpose of part 2, it allows me as an interviewer to better understand the informant's previous experience with virtual reality as a visually impaired user. Therefore, the informant is mostly in control of expressing their opinions about their experience, what works for them, and what aspects of virtual reality are not accessible without me explicitly asking them about certain aspects. It also allows me to better understand the difference between low-vision and fully blind participants. By doing so, the collected data with further help me to structure the most optimal survey for later studies.

Interview guide – Data about user accessibility

In this section of the interview, I aimed to collect data that would help me answer the questions about user accessibility. I attempted to structure open-ended questions yet still focused on specific aspects that I wanted to know more about. Questions structured in a way where I ask the informants, "can you tell me about your experience with spatial audio in virtual reality?" or "can you tell me about your experience with accessibility tools?”. This question allows me to collect data even if the informant did not have any experience with user accessibility tools. Further, as it is a semi-structured interview, I can follow up the answers with more questions about the specific aspect of virtual reality.

Throughout this section, I aim to collect enough data to understand each aspect of virtual reality and its effect on either low-vision or fully blind people.

3.5.3 Ethical Concerns for Interviews

As my research focuses on people with disabilities, it was essential to be respectful toward the participants and not frame the questions in a discourteous manner, in which I assume that the disability affects their use of virtual reality. Before conducting the interview, I would ask the participants if they were open about sharing their disabilities. Thus, I could question how they think their disability affects their experience with virtual reality. As a result of starting the conversation with the agreement from the participants that I could ask questions directly about their disability, it allowed for a more personal and in-depth data collection.

3.5.4 Limitations of Interviews

The most significant limitation that accrued for me during the interviews was missing audio recordings, which either did not occur or did not work. I am aware of the importance and trustworthiness that recordings bring when interviewing, allowing for a complete transcription of the conversation that took place. Unfortunately, I was unable to collect the recordings because of the technical difficulties and/or simply forgetting to turn it on because of the rush a re-scheduling brought with it. However, I still decided to use the interviews in my research, as their primary goal was not to provide the main data collection but to better understand the different groups of visually impaired people and make sure the literature review and actual thought around accessibility in virtual reality were correct. Therefore, the interviews were mainly conducted to build up a more accurate survey, and how the interview did that will be presented in the next chapter. While interviewing, I took notes on my computer to keep an overview of the most crucial topic the interviewees were talking about, also ensuring that I did not forget everything that was said.

3.5.5 Summary – Methodology of Interviews

In this section of the chapter, I have discussed how I went on to interview three visually impaired people who have experience with virtual reality use. I have presented which choices I have made to gather data in a way that will further help me construct the survey. I explained the methods I had chosen to create the interviews, how I selected the informants and the interview guide design. In addition, I have mentioned the ethical considerations and possible limitations during the interview phase. Overall, the interviews provided me with enough data and an understatement of experiences that visually impaired people encounter in virtual reality to further build upon my exploratory sequential design, where I used the data collected from the interviews to create a survey. The collected data from the interviews will be presented in the next chapter, together with data from the surveys.

3.6 Methodology of Survey A

In this section, I will be presenting how I went on to collect data from visually impaired participants through survey A. I will be presenting the choices and methods I took to create the survey and how I selected the informants. Additionally, I will also present and discuss the limitations I came across with survey A, which initially resulted in me creating a new survey (survey B).

Based on the interviews conducted as my first step in the exploratory sequential design, I created “survey A” which aims to collect more data that describes the trends of my research rather than experimental research can. Carswell defines *survey research design* as “procedures in quantitative research in which investigators administer a survey to a sample or to the entire population of people to describe the attitudes, opinions, behaviors, or characteristics of the population” (Carswell, p.376, 2012). I used the survey to collect quantitative numbered data using questionnaires via a web-based survey. A web-based survey allows for gathering extensive data quickly from a more significant number of participants compared to interviews (Carswell, p.383, 2012), which I aim to achieve to answer my research question.

I chose to conduct surveys to collect as much data as possible to answer my research question, “How to make virtual reality standards more accessible for visually impaired people?”. To answer my research question, I had to find out what user accessibility feature visually impaired people find helpful or inaccessible. By collecting data that answers that question, I would successfully identify what needs further development, functioning in an accessible manner, and what aspects of virtual reality do not fulfill user accessibility needs. This sort of data collection can be accessed via a survey, as a more considerable amount of participants answers them Carswell, p.383, 2012).

One important thing I had to be aware of while creating the survey was my focus group. I had to be mindful of user accessibility for the survey I used. Creating a survey with accessible features capable of using screen readers, magnifying tools, or any other accessibility tool that an informant may need to participate in the survey was crucial for me. Therefore, I contacted "Norges Blindeforbunds Ungdom" *Youth of the Norwegian Association of the Blind,* that additionally has a Facebook group named "Nedsatt syn - viktig stemme (brukertester, undersøkelser, forskning m.m)" *Impaired vision - important voice (user tests, surveys, research, etc.).* By contacting the admin of this group, I could source out which survey programs are most user-accessible for visually impaired people. Two web-based programs were mentioned by the group's admin, Google Forms and Survey Monkey. Based on the recommendation from the admin, observation of surveys already posted in the group, and personal experience, I chose Google Forms as my web-based survey program.

I chose Norwegian for the language of the survey, as I intended to share it in Norwegian groups for visually impaired people mainly. I did not identify any differences between creating a Norwegian or English survey, as both would initially provide me with data responding to my research question. Perhaps some phrases or terms would be structured differently. Still, nevertheless, the aspect of creating a survey in the native language for the participants overvalued the possible lack of terms provided in data collection.

I decided for this survey to create open-ended questions for every question. Creswell describes open-ended questions in a survey as "questions for which researchers do not provide the response options; the participants provide their own responses to questions" (Creswell, p.386, 2012). My thought behind this decision was to possibly obtain information specific to each individual. A decision I believe was highly influenced by the interviews I conducted before creating the survey. By creating the open-ended question, I would allow the informant to describe in detail their experience, rather than giving them an option that possibly would not fulfill what they wanted to answer. The consequences of this choice will be further described in the "limitations – Survey A" part of this chapter.

3.6.1 Selecting Participants – Survey A

As I created an open web-based survey, everyone could answer it if desired; however, as my focus group is visually impaired people with experience in virtual reality, I still wanted to narrow it down to that specific group – this was done in two ways. Firstly, I attached an introduction for each survey publication, where I introduced my research and goal. If I posted my survey in a Facebook group, the Facebook post would contain my introduction. In the introduction, I presented my research on identifying what is needed to create a more user-accessible virtual reality for visually impaired people. Therefore, I specified that informants with visual impairments and previous experience in virtual reality would be strongly preferred. However, I also mentioned that informants without either visual impairments or experience with virtual reality were still welcome to contribute. I specified that because some informants may know someone who fulfills that information and would provide valuable data for my research.

Secondly, I only posted the survey in visually impaired communities with permission from the admins of these groups. This automatically narrowed the informants down to where the majority were visually impaired. This method also prevented people outside of my focus group from answering the survey.

3.6.2 Survey Guide

This section will present the survey guide I followed to create the survey, the choices, and their reasoning. Similar to the interviews where I used the "interview guide" with three parts to collect data, I created a "survey guide" that would work similarly. Once again, Carswell's explanation of data gathering is being used, where he explains, "The researcher selects participants and sites, gains permission to conduct the study, decides on the type of data to collect, develops means for recording information, and administers the data collection while anticipating field issues and ethical concerns" (2014, p. 255). Similar to the interview guide, I created a three-part guide for the survey. The first part contains the introduction and presents the first question set to cover the formalities, such as the informant's age and gender, vision impairment, and the number of times they have used virtual reality. The second part of the survey focuses on informants' experience with virtual reality as visually impaired users. Finally, the third part aims to collect data regarding the specific aspects of virtual reality features and tools, such as spatial audio, haptic feedback, and more.

Survey A - Introduction

The first guide part of survey A starts with an introduction, similar to the introduction I posted along with the Facebook posts where I presented the survey for the possible informants. Firstly, I present information about the use of the personal information of the informant, declaring that none of their personal information is acquired for the survey.

"No personal information such as names or email addresses will not be collected, nor shared, or used in any way in this survey. Your identity will stay anonymous, and the collected data will only be used for the purpose of my thesis." (Survey A, 2022).

Declaring that the informant will stay anonymous, especially when my research is asking about their disability, is an essential ethical criterion.

Secondly, I introduced questions that would create a better understanding of the informant, with questions asking about their age, gender, and the number of times they have used virtual reality before. In addition, I asked a question about their visual impairment, which would later help me classify the different experiences and needs for the specific groups of visual impairment, that being either low-vision or fully blind.

Survey A - Previous Experience with Virtual Reality

In this part of the survey, I asked about the informant's experience with virtual reality and their opinions about it. Data collected from these questions would later help me classify the different uses of virtual reality between low-vision or fully blind users. For example, if the majority of low-vision users answer that their use of virtual reality was for video games or entertainment, and wholly blind users only tried to use it but failed, then a piece of important information in my research has been collected.

Survey A - Data bout User Accessibility

The last part of the survey was also similar to the interview guide, where I aimed to gather information about the specific features and tools used in virtual reality. Here I asked questions aimed explicitly toward aspects like "spatial audio" or "haptic feedback" to better understand how low-vision or legally blind groups experience these features or tools. The question would also showcase the difference between low-vision and fully blind and if they find a specific aspect accessible or not.

3.6.3 Limitations of Survey A

In this section, I will be presenting the limitations of survey A, as these impacted my research and resulted in data collection, which I did not find optimal for my research. Firstly, the main limitation I created for myself was opting for open-ended questions in the survey. As I was hoping for responses that would contain the informant's cultural and social experiences instead of my experiences. Something that Creswell states is possible through an open-ended question (Creswell, p. 386, 2012); it was proved to be a mistake to do it for every question in the survey. Creswell describes the strength of a web-based survey to promote a high response rate (Creswell, p.384, 2012) by asking pre-structured answers, such as choosing an alternative created by me as the researcher, or by selecting a number to value a response. When I created a survey containing only open-ended questions, where the informant was forced to type out their full answer, the time required to fulfill the survey limited the number of answers I finished with. After two weeks, the survey collected 13 responses, with in-depth answers, which provided valuable data, but the number of answers was inconsequential to providing enough data for my research.

To avoid the mistake of creating a survey that is not capable of collecting the required amount of data for my research, I could have pilot tested the question before making the survey public.

A pilot test of a questionnaire or interview survey is a procedure in which a researcher changes an instrument based on feedback from a small number of individuals who complete and evaluate the instrument—Creswell, p. 390, 2012.

By first pilot-testing the survey, I could have noticed the amount of time needed to answer the survey. A significant number of questions could have been presented as close-ended questions, where the informant can choose between a set of already created answers.

Another factor that I believe limited my response number was my places of publication. I specifically chose Norwegian visually impaired communities for my respondents, which I believe could be limiting as the number of these groups often does not go over two thousand members. Two thousand members may sound like a lot, but considering factors such as inactive members, the members willing to answer my questions, and my specific criteria of the informants, preferably having experience with virtual reality, drastically narrows the number of responses. However, this can also be interpreted as valuable data; from the two thousand members I presented the survey in which I asked for virtual reality experience responses, only 13 responded. Only 13 responses could also indicate that virtual reality is not a widespread technology among visually impaired people.

3.6.3.1 Result of the Limitations

The result I achieved from survey A was providing me with less data than I preferred to answer my research question in a trustworthy amount. As a result, I decided to edit survey A from an open-ended set of questions into a closed-ended alternative. I also changed the language of the survey to English, which was previously presented in Norwegian. I opened the survey up for a more significant number of responses by changing the language. In addition, I could post the survey on English-based communities for visually impaired people rather than just Norwegian-based.

3.6.4 Summary – Survey A

In this section of the chapter, I have presented and discussed how I went on to create the surveys for my research, where I collected data to understand better the features and tools in virtual reality that are accessible and not accessible for visually impaired people. I go through the choices I made to gather the data, the participants I chose, and the communities I shared the survey with. I also presented the survey guide, which sections the survey into three parts, collecting slightly different data. This section also discusses the limitations accrued based on the choices I made for the survey; as a result of that, I presented the mistakes I believe led to my survey not gathering the wanted amount of data. Finally, I discussed the reasoning for creating a new survey due to the limitations.

3.7 Methodology of Survey B

In this section, I will be presenting how I went on to collect data from visually impaired participants through survey B, and mainly how I changed the survey compared to the first survey. This section is an essential part of the data collection, as it showcases how and why I chose to create a new survey, which became the primary way of collecting data for my research.

Based on the lack of preferred data gathered from survey A, I decided to restructure the questions to collect more responses. Survey A was heavily open-ended, a method that collected in-depth data but with a meager response ratio; in answer to that, I reconstructed survey B into a close-ended survey. By doing so, I would obtain a more considerable amount of response rate as the informants would not have to type each answer out. Therefore, the questions were presented in a way where the respondence had the choice of either selecting one preset answer, multiple preset answers, or a number between 1 and 10, all based on the questions. However, as I value the in-depth data and possibly did not create an optimal alternative to respond to some questions, I included an option for "other" where the informant could write their answer if necessary. An example of this is in question 3, "What type of visual impairment describes your vision loss?". I created ten options for this question from which the informant could choose. According to several sources, these ten answers are based on the most frequent types of vision loss among visually impaired people (WHO, 2021, Coavsion, 2022). Even though I present the ten options for answers, the visual impairment has many more types of vision loss, which would be hard to include in my survey. Therefore, I added the option for "other" where informants can write their answers. As a result, the number of open-ended questions got reduced from 12 to 1.

Changing the language from Norwegian to English allowed me to publish the survey on a larger scale of visually impaired communities. For example, I posted the survey in communities such as Reddit/blind, a community for blind and visually impaired people, with several members of approximately around 16.000 (R/blind, 2022). Learning from my mistakes, I also pilot-tested my survey to ensure the time needed to finish the survey was not limited, allowing for more responses. I used an NVDA screen reader to test the amount of time the survey would take and its accessibility (NV Access, 2022). I also asked my partner to take the survey, as I knew all the questions before testing the time, and I wanted someone without prior knowledge of the questions to provide me with a more accurate response time.

The rest of survey B stayed similar to survey A, such as the questions, which I altered to fit the close-ended alternatives instead of completely changing them. The survey guide also remained the same, as I felt the survey structure provided good results based on the 13 answers I collected from the first survey.

3.7.2 Summary of Survey B

As a result of the survey not providing me with the preferred amount of data to answer and support my research, I created a new survey version. Hopefully, switching the open-ended questions into more close-ended ones would result in more response rates. The results of the survey will be showcased in the next chapter.

3.8 Summary of the Chapter Three

In this chapter, I described the methods of collecting data to help me answer the research question, qualitative and quantitative methods, which results in the so-called mixed method. The mixed method allowed me to create the exploratory sequential design. I used the qualitative method to create a better quantitative method, which hopefully would result in more accurate data collection. Data collection was done by first using the qualitative method, where I used interviews to better understand the main topics each of the visually impaired groups found limiting. These groups are fully blind and low-vision users. By interviewing one person from each group, I could ensure that what I found in the literature review was correct, and I could continue to create survey questions based on the answers. For example, the literature review underlined the importance of spatial audio for fully blind users. Therefore, I asked a fully blind person about spatial audio importance. If the statement correlated with the literature review, I would then perceive to create a survey question about it to gather more data. The same procedure was used to identify the problem between what I found in the literature review and what a visually impaired person found to be a problem. This was mainly done because of the lack of literature review of the topic, and by doing the interviews, I could verify the material found. After the qualitative method, I could go over to create the quantitative method in the form of a survey, which provided me with a more significant number of answers. These answers will be showcased in the next chapter. As a result, I gathered enough data to identify the accessibility problems and limitations for both visually impaired groups, further allowing me to establish possible solutions to answer my research question.

CHAPTER FOUR: DATA AND FINDINGS

4.1 Introduction

This chapter will present the data collected from interviews and surveys A and B. As I was following the exploratory sequential design mentioned in the previous chapter, I will be starting with presenting the data collected from the interviews, then survey A and B. The data collection structure is set to create the best possible data from survey B, which is the primary data collection part of this research. The data collected in this chapter supports the previously presented chapter, where current problems for visually impaired people in virtual reality are presented. Further and more detailed information can be gathered about the inaccessible and accessible parts of virtual reality by collecting the data. Therefore, the data collected in this chapter is essential for the problem-solution section of my research. It identifies the problems that can be addressed in the next chapter.

4.2 Interview Data Collection

In this section of the chapter, I will be presenting the key points of the interviews I conducted with three individuals. Kristoffer Lium, a fully blind digital accessibility expert for the Norwegian Broadcasting Corporation (*Norsk rikskringkasting – NRK)*. Jesse Anderson, St. Paul MN, a legally blind XR user and a member of the XR Access – Virtual, Augmented & Mixed Reality for People with Disabilities. And lastly, a low-vision TikTok content creator who asked to stay anonymous. These interviews provided me with data valuable for creating more detailed surveys by identifying the problems that sight impairments cause for different groups. I especially wanted to identify the differences between fully blind and low-vision people; by doing so, I could create more specific questions for the survey.

I will be structuring the result section around the key themes or topics that emerged from the data analysis. Meaning I will not go into significant detail about every question asked, as the primary purpose of the interviews was to establish a clear difference between fully blind and low-vision users and their current problems in virtual reality. Therefore, the analysis will primarily showcase the essential themes and topics that contributed to building upon the survey, which in the end, was my primary form of collecting data.

4.2.1 Interview #1

The first interview conducted was with Kristoffer Lium, a fully blind, digital accessibility expert for the Norwegian Broadcasting Corporation (*Norsk rikskringkasting – NRK).*

Experience and contrast

When asked about Kristian's prior experience with virtual reality, Kristian acknowledged that his sight impairment limited his prior experience of using virtual reality. However, he had used the virtual reality drawing application, which was not accessible for him apart from the strong contrast: "The only part I could make out was the contrast between colors, but not enough to make anything out of it" (Lium, 2022). This answer provides data that acknowledges contrast use between fully blind users, as some fully blind people still can see colors but in a blurry state. When asked if Kristoffer could describe his vision level, he forwarded me to an article about him from 2018 by Christine Jensen, NRK beta, where his vision state was depicted in this way:

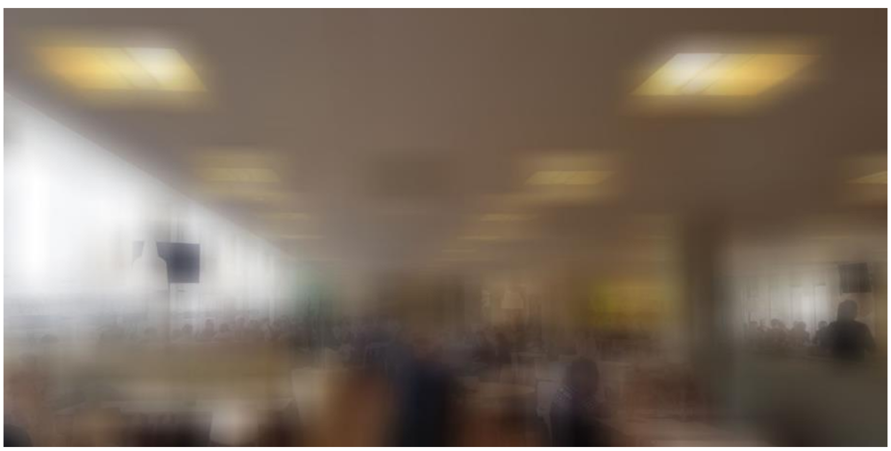


Figure 4.1 – Depiction of Kristoffer's vision (Jensen, NRKbeta, 2018)

When asked about the photo, Kristoffer implied that high contrast and intense light sources are the main parts he can identify; however, he could identify almost nothing other than the contrast. This answer helped me address the contrast topic in my survey, and further solutions for this problem will be presented in chapter five.

Most important accessibility features

When asked about the most important accessibility features that could be implemented in virtual reality, Kristoffer answered with "spatial audio, similarly to how computers and mobile devices work for me, audio is the key feature element when it comes to accessibility" (Lium, 2022). This answer helped me to specifically focus on spatial audio in my survey, as Kristoffer put a big emphasis on audio use. In addition to audio, the text-to-speech was also a vital accessibility feature for Kristoffer, as it is the primary tool he uses to read text displayed on screens. However, the lack of implementation of this feature in virtual reality made it inaccessible for him to use, resulting in his lack of experience in virtual reality.

These two answers resulted in me creating questions for the survey directed to collect data about these two topics, with questions #7 and #8 in survey B collecting data about them. The questions and data collected from the mentioned survey will be presented later in this chapter.

The current state of virtual reality

When asked if Kristoffer believed that virtual reality could become a technology used in the future, based on Meta's plans of implementing it into everyday usage, Kristoffer had two answers. Adding to the importance of spatial audio, the first one was that video meetings could potentially become a more accessible feature for fully blind users:

"…the video meeting, compared to today's Zoom meeting, could be more accessible in virtual reality as spatial audio plays an important role. The current state of the state of audio in a Zoom setting is a 2D audio, meaning that if two people talk simultaneously, they will talk over each other resulting in interruption. The virtual meeting in VR would allow talking to the person sitting next to you without interrupting the main speaker" (Lium, 2022).

Further proof of spatial audio providing accessibility for visually impaired people will be provided throughout the data collected in survey B and the solution in chapter five.

However, Kristoffer mentioned that the current state of virtual reality could be proved challenging to use instead of computers or mobile devices. According to Kristoffer, the current state of screen readers and accessibility in computers is very well developed. With Apple creating the most accessible devices, which could prove difficult to change over to a VR-based technology. Secondly, Kristoffer's other challenging aspects of virtual reality would be the initial setup of the device and the availability based on the price. The answers collected also inspired me to create question number 12 in survey B "Based on VRs current state of development, how willing would you be to use virtual reality (VR) for work or school-related meetings? 0 being very unwilling, 10 being highly willing.". In addition, Kristoffer believes that instead of everyone owning a virtual reality headset, it would become a technology-based more on exhibitions than single man use, where companies could use VR to showcase their product (Lium, 2022).

Overall, the interview with Kristoffer provided me with a better understanding of virtual reality seen by a fully blind person. The interview helped me acknowledge areas that I did not consider valuable for a fully blind person, such as that contrast could still play an important role in virtual reality for them. The interview also supported larger areas of my literature review, such as the importance of spatial audio for a fully blind person. By supporting the literature review, I could create questions in my survey that would allow for a more accurate data collection.

4.2.2 Interview #2

The second interview I conducted was with Jesse Anderson, St Paul MN, a legally blind/ low-vision XR user and a member of the XR Access – Virtual, Augmented & Mixed Reality for People with Disabilities. When asked about his prior experience with virtual reality, Jesse answers that he has been active in the field of virtual reality ever since the technology became available on the market and has excellent and extensive knowledge of virtual reality. His prior experience can be reflected in the answers given later on in this section, resulting in responses that led me to create the surveys. Additionally, answers provided me with significant influence in the solution chapter presented later, as Jessy was part of *SeeingVR*, a toolkit for visually impaired people in virtual reality created by Dr. Yuhang Zhao.

Head tracking and interfaces

When asked about what Jesse found most helpful in virtual reality as a low-vision user, his answer was directed toward the head tracking:

"more specifically, head tracking when I am in a game interface. Not when I am actually looking around in the virtual world, but when I am looking at the pause menu in a game or an application. That could be scenarios like character customization, dialog box, or setting screen. What head tracking allows me to do is to get closer to the text and read the displayed text" (Anderson, 2022).

When further asked if there are any limitations concerning the head tracking in virtual reality, Jesse's response was:

"Yes. Number one would be not having the head tracking enabled throughout the whole experience in virtual reality, as if the option is turned off for some instances, it can become very annoying when I won't be able to move towards a specific menu that popped up on the screen" (Anderson, 2022).

Jesse then followed up by implying the importance of the text displayed on such menus:

> “the problem for us low-vision users is not always how big the text is – that is very important, so is contrast – but the distance is also a big deal. Head tracking allows to move up closer to the text, and if someone has a really bad vision they can really get into it to read it.” (Anderson, 2022).

Head tracking allows the low-vision user to move closer to the text and/or objects in the virtual reality, therefore, I implemented that answer in my survey to further collect data on this statement.

Another problem Jesse addressed was reading text as a low-vision user of virtual reality: “what me and other low-vision gamers are going to have a problem with is actually reading text.” (Anderson, 2022). To address ting problem, Jesse comments that using clear fonts instead of

> “…old English fonts with all the weird loops and tales and things like that, they are artistic, but they’re actually very hard to read, and even more so in virtual reality where text is depending on your distance” (Anderson, 2022).

Jesse also mentions high contrast and large enough fonts being important for accessibility to a low-vision user. These responses were also implemented in creating the questions for the survey, especially in question number 6 where the respondents were asked to identify what they find inaccessible. The data collected from that questionnaire will be presented later in this chapter.

Furthermore, Jesse and I talked about the possible solutions for improving the current problems of virtual reality for low-vision users. He presented to me the studies done by Dr. Yuhang Zhao, which will be presented in chapter five. The interview provided valuable information about the interface problem that low-vision users experience while using virtual reality, a statement that further supports the literature review and the problems mentioned in that section. The interview with Jesse allowed me to better understand accessibility needs for low-vision users, which further built upon creating my survey.

4.2.3 Interview #3

The third interview was conducted with a person who wanted to remain anonymous. However, the interviewee was a low-vision person with significant sight loss in her right eye and lowered vision in her left eye. When asked about her prior experience in virtual reality, the interviewee answered that she owns a virtual reality headset, as her job is content creation around technology. The prior experience ensures me that the answers will be valuable for creating the survey questions. When asked about what the interviewee found mostly inaccessible, the interviewee answered:

"As I have a blend of both lower vision in my left eye, and sight loss in my right eye, there are multiple areas that I find not accessible for me. The biggest inaccessibility for me is reading the text shown on the screen, but also pointing at objects or text is hard as I struggle with depth perception" (Interview, 2022).

The interview further underlines that: "if someone would create a program where I could turn some accessibility options on and off, that would be great" (Interview, 2022). These answers resulted in me creating questions with the option of selecting multiple choices, as the interviewee implied that different disabilities are often present in visually impaired people. The result of these answerers can be seen in questions number 3 and 6 in survey B, presented later in this chapter.

Importance of feedback

Another point mentioned by the interviewee when asked about the accessibility of virtual reality was the lack of feedback provided to the user:

"What really helps me in real life is feedback provided through either feel (haptic) or sound. These help me navigate, either by providing the sense of feel when I can not see everything around me, especially on my right side, or by giving me sound cues that really help me navigate around – I have interacted with sound feedback in VR and found that quite useful actually" (Interview, 2022).

The importance of feedback was therefore included in my survey, with questions 8 and 9 in survey B collecting data about the importance of sound-location cues and haptic feedback for visually impaired people; the data collected from the questions will be presented later in this chapter.

Overall, the interview with interviewee three provided me with a better understanding of the importance of potentially multiple types of disabilities present at one for visually impaired people. The interview allowed me to adjust my question from a single option to a multiple option answer in survey B. The participants would be able to select multiple types of sight impairments that they obtain, allowing for a more precise data collection of which areas are problematic. The more specific and detailed data allows for a better answer to my research question.

4.2.4 Summary of the Interviews

In this section, I will summarize the goal of the interviews and how they affected my thesis. The purpose of the interviews was to better understand the different groups of visually impaired people before creating survey B, which would allow me for a more accurate data collection. By interviewing three members of the visually impaired community, in which each of them had a different type of visual impairment, I managed to collect information valuable enough for me to understand their current limitations in virtual reality better. Furthermore, the information gathered from the interviews provided me with better knowledge and understanding of the needs of fully blind and low-vision users, resulting in me implementing these into the survey presented later in this chapter.

4.3 Survey A

In this section, I will be discussing the reasoning behind survey A and further supporting the choices mentioned in the previous chapter of methodology. As mentioned in the "limitations" sections for survey A in the methodology chapter, the results collected from this survey did not match my expectations. The data gathered from this survey did not prove enough to be considered trustworthy and valuable for my research. However, there was a lesson learned from this survey, and perhaps the data collected from this survey was more in the form of showcasing what I did wrong in it rather than providing data that would help me answer my research question. Overall, even with the lack of data gathered from survey A, it became a practical aspect of my research and resulted in me creating a significantly more precise and valuable survey B.

4.4 Survey B

In this section, I will be presenting the data gathered from survey B – the primary survey and data collection method for this thesis. Using this survey to collect data, I aim to gather information and further support the current problems in virtual reality for visually impaired people in chapter two, the *literature review*. By collecting data from this survey, I will better understand, identify and support the current problems and limitations for visually impaired people in virtual reality. Furthermore, by identifying these problems, one can further address them and create possible solutions to solve them, resulting in a more accessible virtual reality. Therefore, the importance of this survey is significant, and it has the potential to identify the problems for specific groups, significantly underlining the problems which need addressing.

This section will be structured by firstly presenting the questions given in the survey, why the question is essential for the research question and what it aims to collect the data. After that, I will be presenting the data collected in numbers, showcasing the number of participants answering a specific answer. By showcasing the numbers, the survey can establish the importance of a question. For example, when asked if the participants find virtual reality inaccessible, and a significant number of answers is "Yes", one can conclude the answers as "Yes", acknowledging that virtual reality is indeed inaccessible. Lastly, I will summarize the data collected into a conclusion, explaining the collected data's importance and meaning, and tying it to either previously mentioned literature, theories, interviews, or other questions. By doing so, I will be creating a connection between the survey and the previously mentioned content.

4.4.1 Data Collected from Questions in Survey B

Question 1

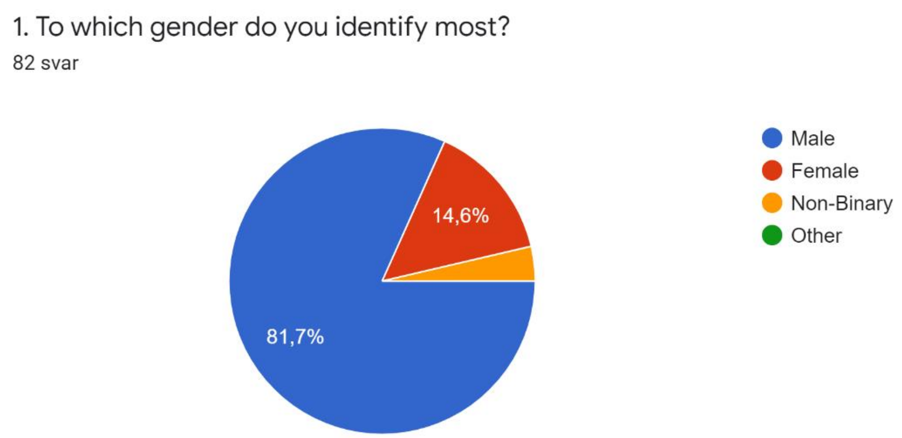


Figure 4.2 – Survey Question 1

Question one of the survey is “To which gender do you identify most?”. This question aims to identify the distribution between male, female, non-binary, or other genders. It is essential to determine the distribution of genders between respondents in the survey as it showcases patterns that can be correlated between virtual reality and other technologies or applications used by different genders. Allowing the respondents to identify between three genders or “other” limits the risks of asking questions that some respondents may find upsetting since the gender-related topic has created mixed emotions among the public.

From the 82 responses gathered from this question, 67 [81,7%] identified as 'Male', 12 [14,6%] identified as female, and 3 [3,7%] identified as non-binary, with 0 respondents identifying as any other gender.

Based on the data collected from this question, the male gender is significantly more present in answering the survey, which could also be interpreted as the gender using virtual reality as a visually impaired user.

Question 2

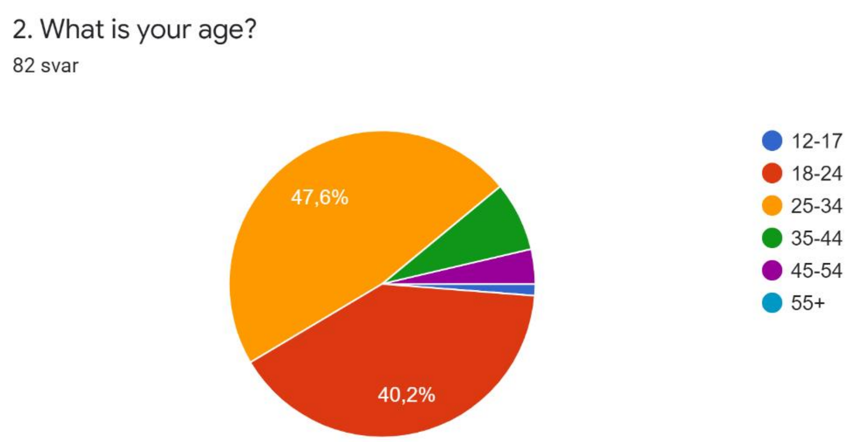


Figure 4.3 - Survey Question 2

Question two of the survey is "What is your age?". By asking the age of the respondents, one can identify if any particular age groups stand out or if a specific age group is proven to be more prevalent in the research topic than others. This can further develop into the research, as audience targeting can be based on age; this is further supported by Facebook, where their target age is between 13 to 65+ (Facebook, 2022), a factor which is relevant for this research as Meta is creating a more significant focus on virtual reality.

From the 82 responses collected from this question, the age group '25-34' is the leading group, with 39 [47,6%] respondents in that age group. The age group '18-24' with 33 [40,2%] respondents, the age group '35-44' with 6 [7,3%] respondents, the age group '45-54' with 3 [3,7%], and the age group of '12-17' with only 1 [1,2%] responses, The age group '55+' had no respondents in my survey.

Question 3

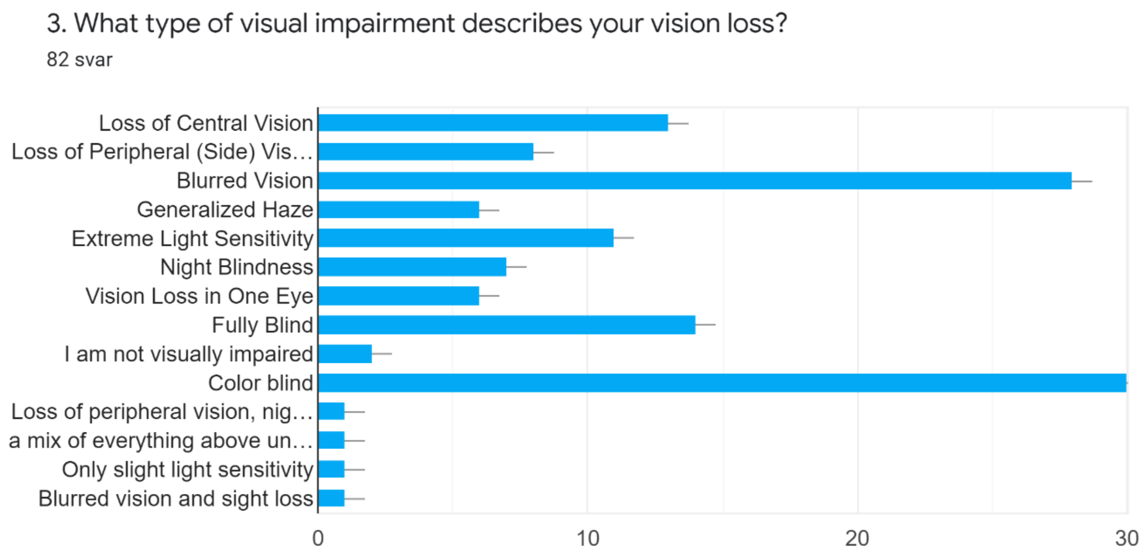


Figure 4.4 - Survey Question 3

The third question of this survey is, "What type of visual impairment describes your vision loss?" This question was created to identify the type of vision loss the respondents identify as. These responses allow me to further classify them into either a 'low-vision' or 'fully blind' category, which later can be tied to the rest of the responses gathered throughout the survey.

This question allowed the respondents to choose between multiple choices, as visually impaired people often tend to experience various types of vision loss at once. In addition, this question also included a section where respondents could type in their specific type of vision loss which I did not list; this allowed me to gather more detailed data and potentially uncover vision loss that I did not anticipate being impactful on the use of virtual reality.

The results of this question showcase that 'Color Blind' is the most picked type of vision loss among my respondents, with 30 [36,6%] out of 82 choosing this answer. 2nd most answer choice with 28 [34,1%] is 'Blurred Vision'. Then 'Fully Blind' with 14 [17,1%], 'Loss of Central Vision' with 13 [15,9%], and 'Extreme Light Sensitive' with 11 [13,4%]. The answers between 6 and 8 were 'Loss of Peripheral (side) Vision' 8 [9,8%], 'Night Blindness' 7 [8,5%], and both 'Generalized Haze' and 'Vision Loss in One Eye' receiving 6 [7,3%] answeres. Only 2 [2,4%]

responses were ‘I am not visually impaired. Moreover, the rest of the responses were written by respondents individually.

Question 4

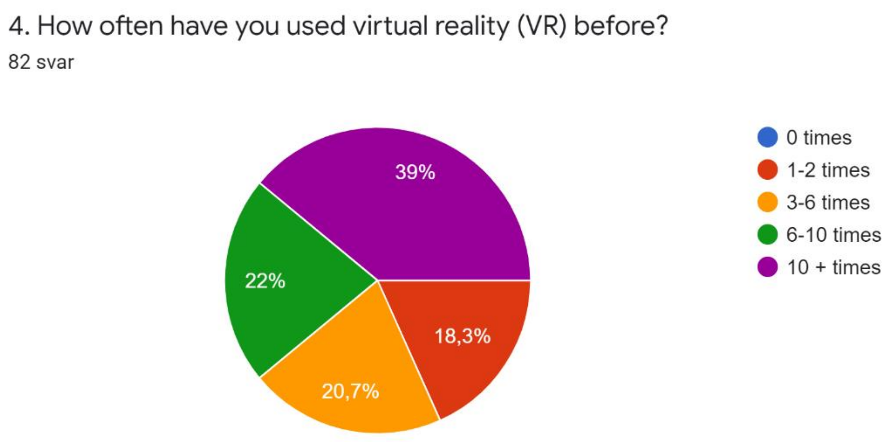


Figure 4.5 - Survey Question 4

This question asks, “How often have you used virtual reality (VR) before?”. This question aims to collect data for two factors. Firstly, it displays the trustworthiness and quality of the responses collected by showcasing how often the survey respondents have used virtual reality technology. The rest of the data can be more accurate based on the survey respondents’ time using virtual reality. It allows for higher accuracy, followed by the number of times the respondents have used virtual reality. Secondly, it showcases how popular virtual reality is among visually impaired people.

The data collected from this question showcases that 32 [39%] out of 82 respondents have used virtual reality ‘10+ times’, then 18 [22%] respondents have used virtual reality ‘6-10 times’, 17 [20,7%] respondents ‘3-6 times’, and lastly 15 [18,3%] respondents have used virtual reality only ‘1-2 times’. No respondents have answered that they never used virtual reality with the ‘0 times’ option.

One limitation of this question is what “used” means and how much or detailed the usage of virtual reality was for the respondent. For example, one respondent answering ‘3-6 times’ could only have tried virtual reality for a couple of minutes each time, while someone who only tried it once could have used it for hours, gathering more insightful and valuable data. Another partial limitation with this data at first glance is the lack of information about which group of visually impaired people selected ‘1-2 times’ and which group selected ‘10+times’. Looking at the appendix, the data becomes more informative. 7 out of 14 participants identified as ‘fully blind’ selected ‘1-2 times’, then 5 out of 14 ‘fully blind’ selected ‘3-6 times’, and the rest (2) selected ’10+ times’. By acknowledging this information, we can further conclude that majority who select ‘10+ times’ are visually impaired people with the low-vision type of disability, and those who only use virtual reality ‘1-2 times’ are fully blind. As a result, one can argue that virtual reality is perhaps more accessible for the low-vision user rather than the fully blind user.

Question 5

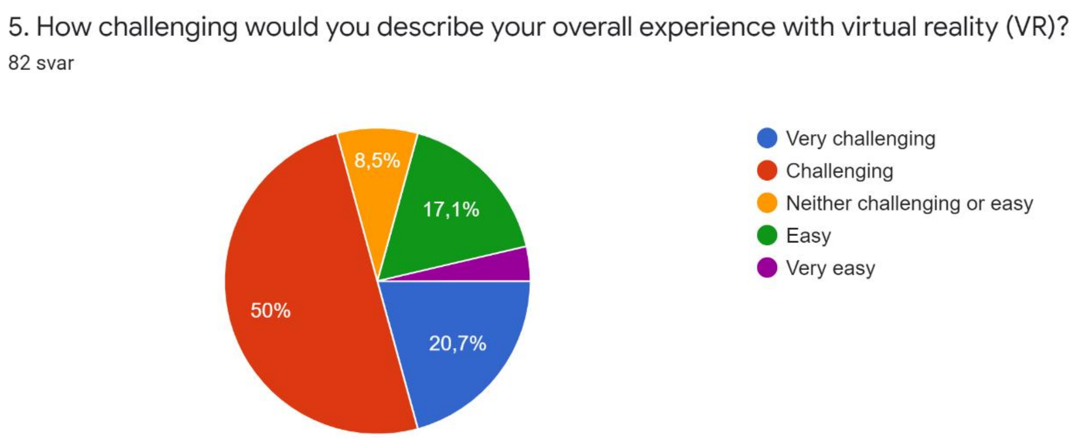


Figure 4.6 - Survey Question 5

The fifth question is ‘How challenging would you describe your overall experience with virtual reality (VR)?’. This question aims to highlight the overall difficulty with virtual reality for visually impaired people and whether they find the technology challenging for them or not. This data can highlight one of the main points of the research question, underlining that the majority of the respondents find virtual reality challenging. It can be because of accessibility lack or other factors which have not been addressed enough to create accessible virtual reality for visually impaired people. The data collected from this question displays vital information for developers and companies working on virtual reality; by analyzing this data, a clear point can be proved that virtual reality is either challenging or not for visually impaired people.

As the result of the data based on 82 answers, half of the respondents, 41 [50%], found virtual reality to be ‘challenging’, and a further 17 [20,7%] respondents found it ‘Very challenging’. This makes up to 58 [70,7%] out of 82 respondents who found virtual reality to be a challenge to use, with only 14 [17,1%] finding it ‘easy’ and 3 [3,7%] ‘very easy’.

Question 6

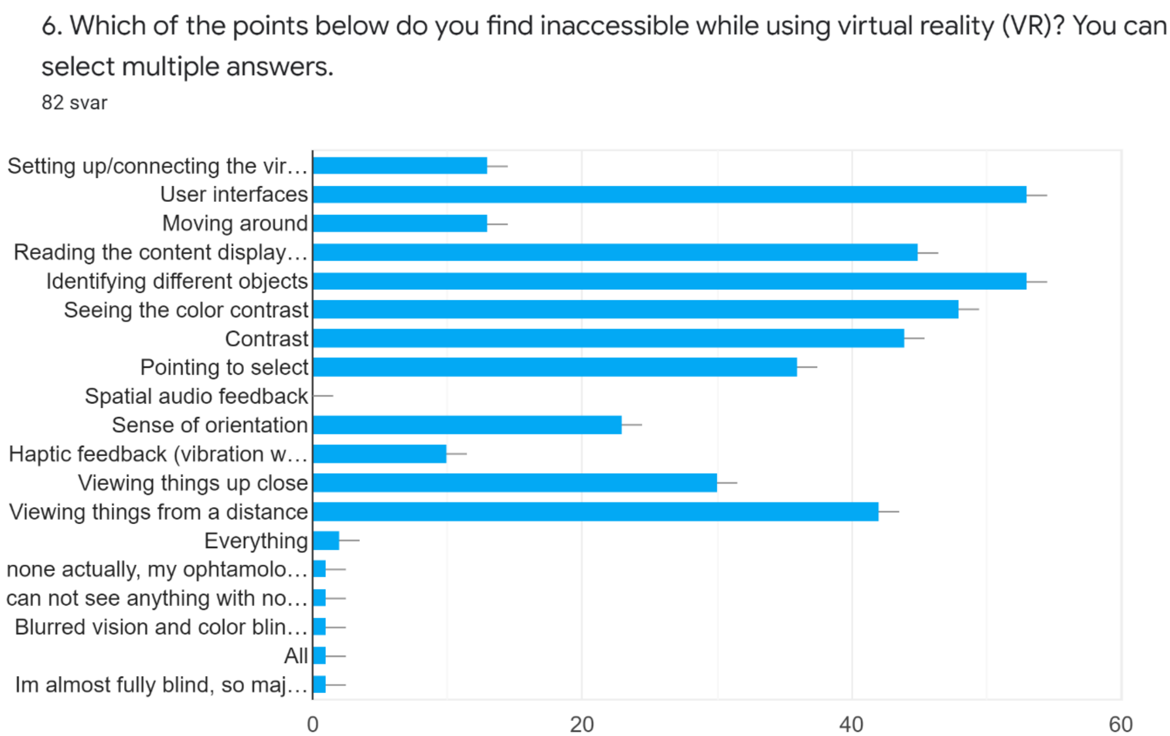


Figure 4.7 - Survey Question 6

As ‘question 5’ acknowledges whether virtual reality is challenging or not, the current question 6 follows up that question by asking, ‘Which of the points below do you find inaccessible while using virtual reality (VR)?’. The data collected from this question highlights the features or tasks visually impaired people find inaccessible. In addition, one can argue that the question also highlights the features or tasks of virtual reality which are accessible. The inaccessible features are the ones collecting the data by user answers, displaying specifically inaccessible features with higher numbers highlighting the most features primarily inaccessible. As a counterargument, the features with the least votes can be argued to be the most accessible out of the provided list. This question and data are highly relevant to my research topic. Identifying what is inaccessible for visually impaired people could showcase what needs to be more addressed to make virtual reality accessible for visually impaired people.

To better understand and create a scope over the inaccessible parts of virtual reality, this question allowed respondents to select multiple options, as it would provide a better picture of the overall inaccessible parts of virtual reality. Two responses shared the first place of being categorized by visually impaired people as inaccessible; ‘User interfaces’ and ‘Identifying different objects’ both shared 53 [64,6%] votes. This is crucial information for the research, as interfaces and generally identifying objects can be a sign of multiple factors contributing to these features or tasks being inaccessible, such as lack of text to speech, magnifying, or others mentioned earlier in this paper. The collected data also showcases large popularity in ‘Seeing the color contrast’ with 48 [58,5%] responses, ‘Reading the content displayed on the screen with 45 [54,9%] responses, ‘Contrast’ collecting 44 [44%], and ‘Viewing things from a distance’ with 42 [51,2%] responses. This question also had an alternative for respondents to write their own answers, as I wanted them to showcase the features or tasks I might have forgotten to mention. This option received five answers that can be summarized as an “all” option, an option in which I did not include myself but was able to be used by writing an answer for the respondents.

Like the questions showcased earlier in this chapter, question number 6 can be interpreted differently based on the type of vision impairment a respondent has. For example, the majority of answers containing ‘Contrast’ or ‘Seeing the color contrast’ were received from respondents whose visual impairment type is ‘Color blind’ or ‘Blurred vision’ (appendix ?)

Questions 7, 8 and 9

These three questions have a similar setup and aim to collect data precisely about one concentrated feature for each of them. All three are questions where the respondents are asked to rate how essential a specific feature is for them from 0 to 10, where 0 is not essential, and 10 is significantly essential. The three questions aim to collect data based on research I collected through the literature review for this thesis, where certain features stood out to me. Zhao et al. (2018, 2019) mention sound-location cues and haptic feedback as the primary navigation tools for visually impaired people using their *Canetroller* and screen reader or “text to speech” tool in *SeeingVR* as an effective tool (Zhao, 2018, Zhao, 2019). Based on the literature review and research done by Zhao and her team, I created the questions collecting the essentiality of ‘screen reader’, ‘sound-location cues’, and ‘haptic feedback’, to further support Zhao's research in addition to my research

question.

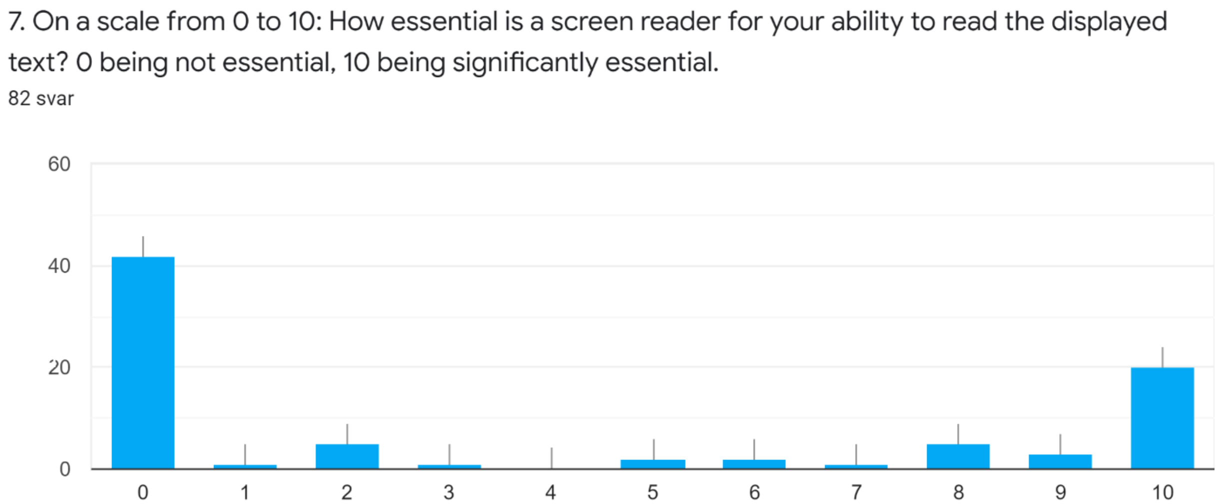


Figure 4.8 - Survey Question 7

Question 7 in the survey is ‘How essential is a screen reader for your ability to read the displayed text?’. Keep in mind that I did not specifically ask for screen readers in virtual reality, as based on the research from the literature review, this feature is non-existing in virtual reality. Therefore, I left the question open to let the respondent interpret the question as screen-readers in general, not only in virtual reality. (I am aware of the mistake of perhaps not making it more apparent that the question is not focusing on virtual reality). As a result, 42 [51,2%] did not find screen readers essential by answering ‘0 – not essential’, with 7 additional respondents fluctuating around the ‘not essential’ side, with 1 [1,2%] responding ‘1’, 5 [6,1%] responding ‘2’ and 1 [1,2%] responding ‘3’. Then, 20 [24,4%] respondents find screen readers ‘significantly essential’, with additional 11 [15,8%] respondents fluctuating between 9 to 5 options.

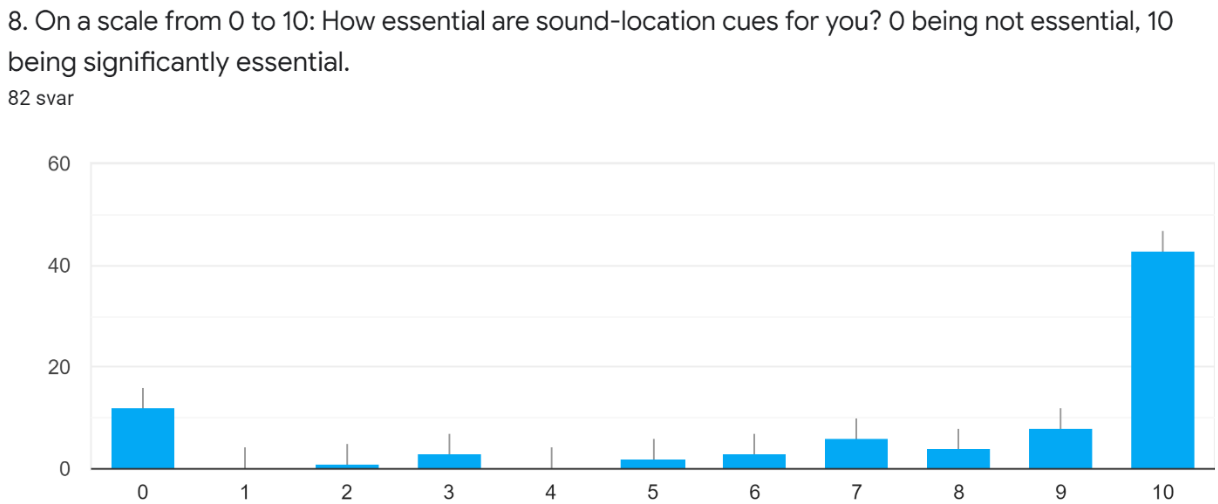


Figure 4.9 - Survey Question 8

Question 8, similarly to question 7, aims to identify how essential ‘sound-location cues’ are. As mentioned previously in the paper (*Spatial audio and sound effect,* chapter 2), sound can be one of the most helpful tools for visually impaired people as it often indicates important cues. Question 8 sets to identify the number of respondents finding sound-location cues essential to further support this theory. From the 82 responses gathered in the survey, 43 [52,4%] of the respondents answered ’10 – significantly essential’, with an additional 23 [28,1%] respondents fluctuating between answers ‘5’ to ‘9’, making a total of 66 [80,5%] of respondents acknowledging ‘sound-location cues’ as essential in some sort of level. Only 12 [14,6%] found ‘sound-location cues’ not essential. This result further supports my and Zhao’s research that sound location is an important feature for visually impaired people.

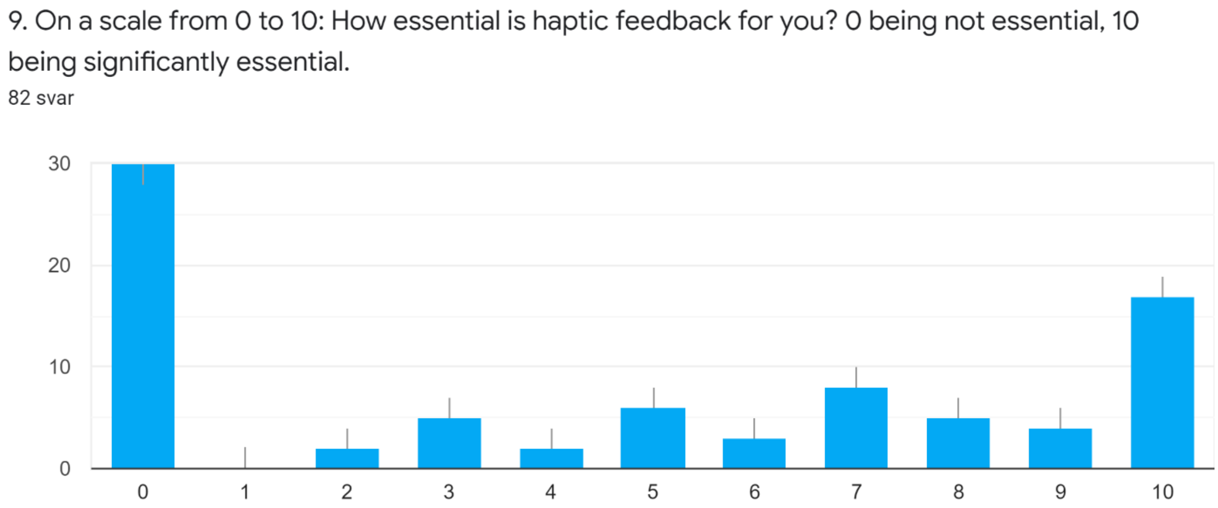


Figure 4.10 - Survey Question 9

Question 9 aims to collect data on 'How essential is haptic feedback for you?'. Similar to the two previous questions, it is based on Zhao et al. research of the *Canetroller*, where Zhao highlights the importance of haptic feedback, especially for fully blind users. To further support this theory, this question aims to measure the essentiality of haptic feedback.

The question results showcase 30 [36,6%] of the 82 participants responding that haptic feedback is not essential for them, with '0' as their answer. On the other end, 17 [20,7%] answered that haptic feedback is significantly essential for them by answering '10'. In addition, 26 [31,8%] other participants answered that haptic feedback is essential to them, to a certain degree between '5' to '9', with a total of 43 [52,5%] that find haptic feedback essential.

Similar to other questions in this chapter, question 9 can also be acknowledged better by identifying which groups of visually impaired people responded to particular answers. For example, looking at the appendix, the respondents who selected that haptic feedback is essential for them are mainly 'fully blind' or have 'loss of central vision, which no 'fully blind' respondents answered under 5, and 11 out of 14 'fully blind' selecting '10' as an answer. In opposition, as an example, 16 out of 30 responses answering '0' were 'Color blind'. Therefore, this collection of data explicitly showcases which groups find haptic feedback essential, further supporting the statement of Zhao (Zhao, 2018) and answering my research question.

Questions 10 and 11

Throughout the survey, the participants have identified which scenarios in virtual reality are inaccessible for them and how certain essential features based on my prior research are for them. Questions 10 and 11 are aimed to follow up on the previous question and seek to identify one specific feature the user would find MOST and LEAST practical for them. The results of these questions are essential to identify further the features that may need to be addressed as essential and underline the features that are not critical for people with vision impairments. This can further help my research by identifying the needs. Both questions have the same answers possible to be selected, with the additional possibility of writing an answer if the respondents choose so. Still, only one answer can be selected for both..

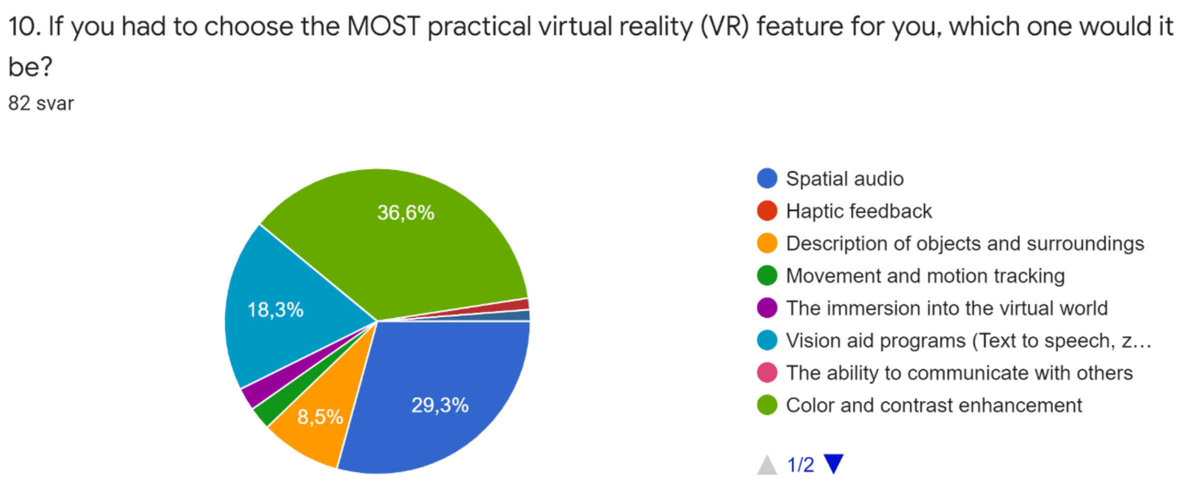


Figure 4.11 - Survey Question 10

Question 10 aims to identify 'the MOST practical virtual reality (VR) feature'. Three answers stand out among the collected data, with 'Color and contrast enhancement' receiving the most answers, with 30 [36,6%] out of 82 choosing it. Then 'spatial audio' with 24 [29,3%] responses, and the third answer with the most answers were ' Vision aid programs (Text to speech, zoom in) with 15 [18,3%] answers. Based on these answers, we can compare with Zhao's, where *SeeingVR* (Zhao, 2019) creates tools for 'color and contrast enhancement and 'vision aid programs (Text to speech, zoom in)'. In addition, *Canetroller* (Zhao, 2018) highlights the importance of spatial audio. Furthermore, based on the data collected, we can identify the answers of both visually impaired groups, low-vision and fully blind. There, low-vision respondents tend to answer 'color and contrast enhancement and 'vision aid programs (Text to speech, zoom in)'. And fully blind respondents choose 'spatial audio' as their answer. This is highly based on their needs, further supporting the importance of this research study.

In addition, the question is not explicitly asking for 'already implemented features in virtual reality', which indicates the features that visually impaired people would want to be implemented in the further development of virtual reality.

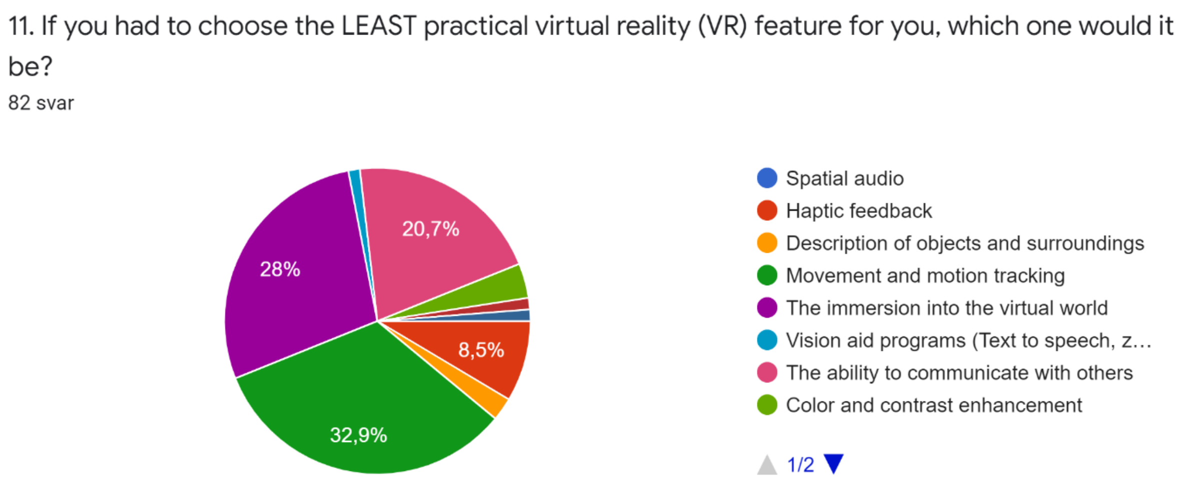


Figure 4.12 - Survey Question 11

In opposition, question 11 of the survey asks for 'the LEAST practical virtual reality (VR) feature'. This question aims to collect data about the features that visually impaired people do not find important in virtual reality. This may sound less useful than the other questions. However, it might be one of the more essential questions for this paper. The result of this question supports the theory of *critical disability* and especially the *design-in-use* theory. Since virtual reality is mainly developed by abled people, without feedback from disabled/visually impaired people under the development, it can result in the abled developers focusing on what they think is most important. This often leads to user accessibility not being prioritized, making virtual reality less accessible for visually impaired people.

Similar to question 10, this question has three central answers. First, the least practical feature for visually impaired people based on 82 answers, 'movement and motion tracking' with 27 [32,9%]

answers. The second most answered option is ‘the immersion into the virtual world’ with 23 [28%], and the third is ‘the ability to communicate with others’ [20,7%].

This data shows that ‘movement and motion tracking’, the immersion into the virtual world’, and ‘the ability to communicate with others’ are the least practical features for visually impaired people. One can argue that these selected features, in opposition, are the ones most talked about when developers talk about the feature of virtual reality. It further supports the critical disability theory and the importance of visually impaired people being included in the design and development of future technology.

Question 12

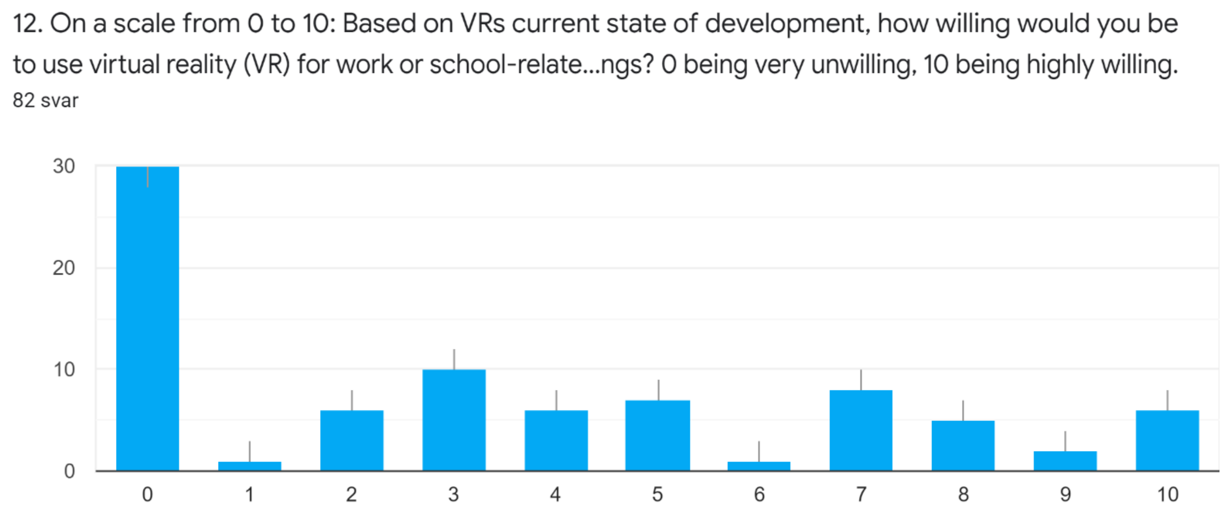


Figure 4.13 - Survey Question 12

The twelfth question towards the end of the survey asks ‘On a scale from 0 to 10: Based on VRs current state of development, how willing would you be to use virtual reality (VR) for work or school-related meetings? 0 being very unwilling, 10 being highly willing’. This question is essential based on Meta’s comments about their plans for *Metaverse*, where Meta remarks on the possibility of attending work, school, or social gatherings through virtual reality and seemingly develops that thought into a regular feature. Based on these comments, it is essential to ask if the current virtual reality is enough developed, accessible, and generally in a sustainable position for visually impaired people to consider its use for work or school meetings. Based on the answers, one can argue if virtual reality needs further development and addressing problems to make it accessible for visually impaired people.

The result gathered from the data highlights that 30 [36,6%] of respondents are not willing to use virtual reality for work or school meetings based on the current state of its development. Furthermore, an additional 30 [36,6%] respondents answered in the ‘unwilling’ ratio, from ‘1’ to ‘5’, making a total of 60 [73,1%] respondents not willing to use virtual reality for work or school meetings based on the current state of VR. In opposition, 22 [26,9%] of the respondents are willing to use virtual reality for school or work meetings.

Similar to other questions, we can compare the answers based on the visually impaired groups. Not a single ‘fully blind’ respondent has answered that they are willing to use virtual reality in its current state for work or school meetings (appendix ?). The majority of the answers selected as ‘10’ belong to respondents which have the ‘Color blind’ impairment.

The results of this study further support both of my theories; critical disability theory showcased the importance of having disabled people in “power”, where they can contribute to the development of virtual reality. Furthermore, the design-in-use theory showcases the development of technologies that can limit visually impaired users simply because a company decides that this technology will be used for work or school meetings.

Question 13

The survey’s last question is ‘Overall, would you say that virtual reality has an accessibility problem limiting its potential for visually impaired users?’. This question aims to summarise the inter content of the survey into one last question, which builds on the previous questions to try and answer of has a significant accessibility problem for visually impaired people. This question is essential for my research, as its answer is often unknown, especially for developers. By collecting data that proves one side, this answer can showcase a statemate that is often unknown or ignored, shining light on the topic and hopefully addressing the problem in the further development of virtual reality.

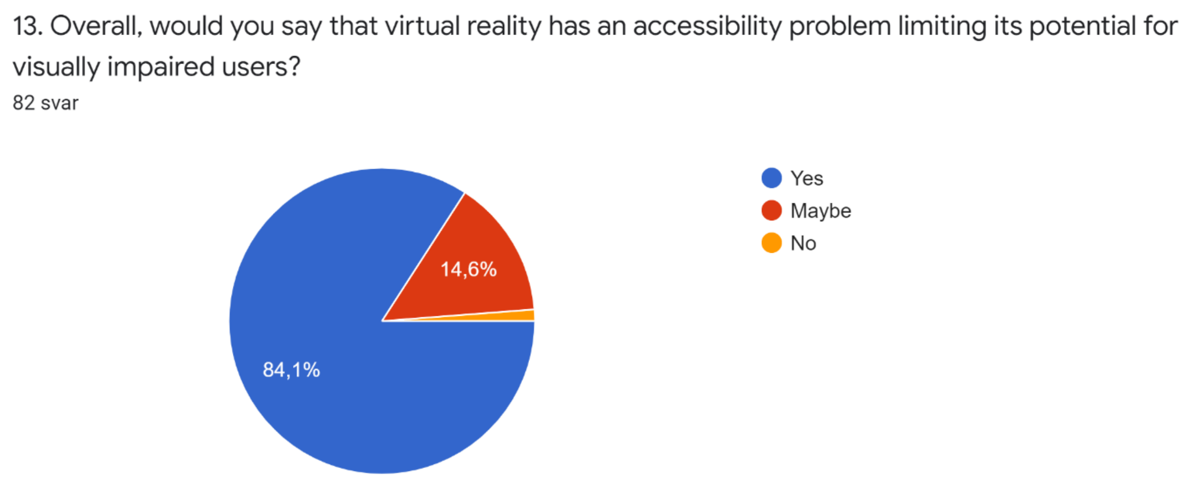


Figure 4.14 - Survey Question 13

The data collected through this question showcases an explicit agreement between the survey respondents, with 69 [84,1%] out of 82 respondents answering 'Yes', and 12 [14,6%] answering 'Maybe'. That leaves only 1 [1,2%] respondents who answered 'No'.

The result of this question showcases that most visually impaired people find virtual reality to have an accessibility problem, limiting the potential for the visually impaired users to use this technology fully.

4.5 Summary of Survey

The data collected from this survey further supports the "problems" presented in the literature review and the theories presented at the beginning of the thesis. The data collected showcases the inaccessibility of virtual reality for visually impaired people, with significant data differences between fully blind and low-vision users. The survey partially supports the research question, as it confirms that virtual reality has a user accessibility problem for visually impaired users. The survey result can be summoned up in two categories, one category for fully blind users and one for low-vision users. Data shows that fully blind users tend to value spatial audio and haptic feedback to a more considerable extent, features, and tools that substitute the lack of sight.

On the other hand, low-vision users tend to lean more toward features and tools that enhance their partially functioning sight. In conclusion, survey B further supports the previously mentioned problems and underlines the importance of creating at least two different accessibility solutions for visually impaired people. The difference between fully blind and low-vision users is significant in terms of what features and tools they use need.

CHAPTER FIVE: SOLUTIONS

5.1 Introduction

This chapter will introduce the possible solutions for creating a more accessible virtual reality for visually impaired people. The solution is based on the previously introduced literature review chapter and the data collected from interviews and surveys presented in chapter four. Presenting the following solutions have multiple factors that are important for the research question of this thesis. Firstly, the solutions support the need for accessibility for visually impaired people in virtual reality by addressing current problems and working towards solving them. Secondly, the solution supports my research and data collected for this thesis, as there is a coloration between the collected data and the solutions which will be presented. Lastly, the solutions present the current state of accessibility awareness for visually impaired people in virtual reality, the amount of already created solutions, and the level to which these solutions are further used.

To fully answer the problems presented in the previous chapter, I will be addressing them by presenting solutions based on the research studies done by Dr. Yuhang Zhao named "Designing Technologies to Make Virtual Reality Accessible for People with Visual Impairments" (xraccess, 2021). These two main studies of Canetroller and SeeingVR will present a possible solution of accessibility measures implied in virtual reality to create a more accessible experience for both groups of visually impaired people, the fully blind low-vision groups. Firstly, I will be presenting the *Canetroller*, a virtual controller built to transform the white cane techniques of a fully blind user into the virtual world. Doing so allows the user to physically navigate the virtual space. First, I will present how Canetroller works, and the data Zhao and her team collected from the studies conducted using their technology. Secondly, I will be presenting *SeeingVR*, a set of tools created to increase various accessibility points limiting the current state of virtual reality and mainly focusing on addressing the accessibility features for low-vision users.

Showcasing *Canetroller* and *SeeingVR* is crucial for my thesis, as it supports the problem-solution structure of the paper. By presenting possible solutions, I will enforce that creating a more accessible virtual reality for visually impaired people is possible. Therefore, addressing the previously mentioned problems, supported by my collected data and the theories, shows that this research is essential.

The structure of this chapter is as follows; introduction of the research, then a section about the Canetroller where its study and method will be presented, followed by how the *Canetroller* functions, how it enforces my previously mentioned points, and at the end, a study of the use of *Canetroller*. The second section will present SeeingVR, starting with how it works and aims to create more accessibility in virtual reality by using multiple tools, followed by the part created for the developers, and ending with a study of both *SeeingVR* for low-vision users and the developers. Finally, towards the end, I will mention other possible solutions that could be mentionable for creating a more accessible virtual reality and end the chapter with a summary.

5.1.1 Research Introduction

Dr. Yuhang Zhao is an assistant professor in the Department of Computer Sciences at the University of Wisconsin-Madison (xraccess, 2021). Her research fields are Human-Computer Interactions (HCI), accessibility in augmented reality and virtual reality, human-centered AI, and mobile interactions. With builds of design and intelligent interactive systems to enhance human abilities (XR Access, 2021). In her research on “Designing Technologies to Make Virtual Reality Accessible for People with Visual Impairments,” in collaboration with Microsoft Research. They created two possible solutions to improve virtual reality by making it more accessible while still providing an authentic, immersive experience to enable visually impaired people to freely explore the virtual space (XR Access, 2021). With her work of designing *Canetroller* – “a haptic controller to enable people who are blind to navigate virtual space,” and *SeeingVR* – A design set of tools to make virtual reality more accessible for people with low vision (Zhao, 2018).

A study using the created solution will support each possible solution, displaying its effectiveness in creating a more user-accessible virtual reality. Based on my literature observation and gathering throughout my research, I would consider the solutions developed by Zhao to be the main ones in the field of accessibility of virtual reality. Moreover, they are one of the few, if not the only, solutions addressing visual impairment. Therefore, these two solutions are foremost essential to present for my research, with possible solutions to further provide solutions answering my research questions.

5.2 Canetroller

This section will present the Canetroller, providing a possible solution for the fully blind virtual reality users. I will start by introducing Zhao's study of blind users and mobility instructors, which led to the design of the Canetroller, and the methodology Zhao used for interviewing the participants. The study is essential for the design choices implemented in creating the *Canetroller*. *This section* will also be presented in this chapter, where I will go into detail about how the *Canetroller* works, how it works in a correlation to accessibility, and how it answers my research question.

The design goal of the *Canetroller* is to create a virtual reality controller which can transform cane techniques into the virtual world, enabling visually impaired people to ***physically*** navigate the virtual space more comprehensively (Zhao, 2018). As mentioned in chapter three, using a cane by visually impaired people is one of the most common ways to navigate the real world, a technique that Dr. Yuhang Zhao is trying to implicate in virtual reality. By doing so, Zhao aims to reuse and leverage the skill of using a cane that visually impaired people already have, resulting in a lower learning curve instead of learning utterly new technology and interaction techniques (Zhao, 2018).

5.2.1 Zhao's Study and Method of Canetroller

This section presents the study conducted by Zhao and her team before creating the *Canetroller*, which allowed them to better understand the use of real-world white cane usage by visually impaired people. Zhao also asked about their prior experience with virtual reality, similar to how I asked my participants in the interviews and surveys, to better understand how fully blind and mobility instructors experience virtual reality.

A formative study was first conducted for the research of *Canetroller*, with seven white cane users and five mobility instructors. The study's goal was to study their expectations and prior experiences with the use of virtual reality. Furthermore, to study their white cane use in real life and if there was a possibility to transfer that skill into the virtual world. For the interview, Zhao asked about their understanding of virtual reality, their prior VR experience, and their expectations of VR. For the side of cane use, Zhao asked about their use in real life and then asked if the percipience could navigate with their canes while Zhao observed their cane strategies in five different scenarios (Zhao, 2018).

Scenarios that were observed were "(1) the experiment room with desks, chairs, and trashcans; (2) a corridor from the experiment room to an elevator; (3) an outdoor area surrounded by circular cement seating platforms; (4) a street crossing area with tactile domes; (5) a square sand sports pit surrounded by curbs, with two benches and a metal trashcan outside of the area." (Zhao, 2018).

For the mobility instructors, Zhao asked about their prior knowledge of VR applications for visually impaired people, the potential of virtual reality, and for them to describe standard cane skills, training techniques, and the main training scenarios (Zhao, 2018).

5.2.2 Zhao's Interview and Observation Results

This section presents the results of the interviews and observations by Zhao, data which further supports the design of the *Canetroller.*

Expectations

VR showed high interest in virtual reality among the visually impaired people and mobility instructors, who envisioned virtual reality as a mobility-training platform. Where users could simulate routes or unfamiliar environments to learn cane skills, prepare for travel, and further build confidence, using VR as an educational tool. Some even hoped that VR would be able to bring them equal access to all visual information that they could never perceive before (Zhao, 2018). Similar expectations which I presented earlier in this paper. Mobility instructors expected virtual reality to be a training and rehabilitation tool for visually impaired people, with a possible reduction in the funding limitations that both their organization and clients can experience in the form of time as a resource. The use of virtual reality could also be proven to simulate different scenarios, especially scenarios that can be found risky and dangerous for visually impaired people and mobility instructors, such as walking down a set of stairs or crossing a street (Zhao, 2018).

"*Funding does not always allow ideal training amounts*"

– Mobility instructor (39, f), (Zhao, 2018).

Use of a cane

Zhao performed observation to identify the most suitable techniques for using the white cane. Both tactile (haptic) and audio feedback were the main ways of using the white cane to explore the real world. Audio and tactile feedback provide sound when the cane knocks into different environments or is swept on different textures like concrete or carpet, helping the visually impaired people navigate (Zhao, 2018). Observation of three techniques commonly used by people using white canes was made. *Two-point touch* is tapping the cane left-right-left-right in front of the user’s body to identify possible obstacles, primarily used in an environment known for the cane user (Zhao, 2018). *Constant contact* is sweeping the cane from side to side and always keeping the cane tip in connection with the surface, primarily used in an unknown environment for the cane user (Zhao, 2018). *Finally, Shorelining* is a technique that uses touch and drags to travel along an edge, often used by cane users when walking near a wall, “*it can protect the other side of your body*” - Mobility instructor (Zhao, 2018).

Results of interviews and observations

Based on the interviews and observations that Dr. Yuhang Zhao and her team performed, a design implication for the *Canetroller* could be structured with two main design implications. First, to support multimodal feedback when designing technology specifically on the controller, to enable blind people to explore virtual space. This would be done by providing audio and tactile feedback through a *Canetroller* for people to better understand the virtual world, similar to how they explore the real-world environment. Secondly, stimulating the standard cane techniques enable cane users to directly transform their real-world skills into the virtual world, resulting in lowered cognitive lead and learning form instead of learning new technology or interaction techniques from scratch (Zhao, 2018).

5.2.3 Canetroller: a Wearable VR Controller

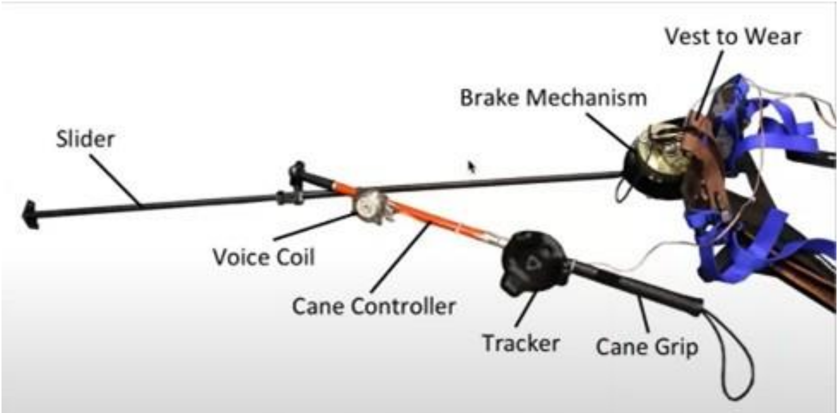


Figure 5.1 – The Components of *Canetroller* (XR Access, 2021)

Figure 5.2 – A Woman Using the *Canetroller* (XR Access, 2021)

This section describes how the *Canetroller* is built and how it addresses the need of fully blind users, by providing different aspects of accessibility to create feedback that stimulates the similarities with a white cane used in real life.

Based on the design implications found by Zhao and her research team, they created a wearable virtual reality controller for visually impaired people to use in virtual reality. The *Canetroller* is constructed of multiple components, as shown in *figure 5.1*. The *Canetroller* can be attached by a wearable belt shown in *figure 5.2,* together with a brake mechanism and a controller itself is a shortened down white cane that users are familiar with using in the real world. However, it is cut short to avoid coming in contact with any real objects in the physical environment. The cane also has a voice coil that generates vibration and a tracker device to transfer position tracking into virtual reality.

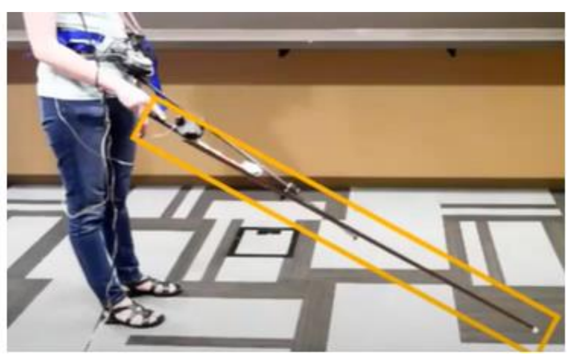


Figure 5.3a – Cane controller seen in real life (short) **Figure 5.3b** – Cane controller seen in VR (actual size of a cane) (XR Access, 2021)

The cane controller is also connected to a slider, making a 360° motion possible for the user of the *Canetroller* (Zhao, 2018). As seen in *figure 5.2*, the woman is wearing a head-mounted display; In contrast, the visual display does not provide any information as the users are mostly fully blind. It provides them with spatial audio to help navigate and understand the virtual space.

The cane controller is shorter than in real life, as showcased in *figure 5.3a*, mainly to prevent the cane from accidentally hitting real objects in the physical world. However, it is represented as a standard-length cane in the virtual world, as shown in *figure 5.3b* (Zhao, 2018).

Multimodal Feedback

The *Canetroller* provides three types of feedback to create the most optimal experience for the user: *Physical resistance, vibrotactile feedback,* and *spatial auditory feedback* (Zhao, 2018).

Physical resistance demonstrates how users feel the physical resistance in the real world when hitting an obstacle in the virtual environment; when the connection happens, the brake mechanism locks itself and stops the movement of the slider to which the cane controller is attached. Creating physical resistance results in the user feeling the force feedback and not being able to move the *Canetroller*, simulating the same experience as when a cane hits a real object. For example, *figure 5.4* showcases a virtual plastic trashcan; when contacted by the *Canetroller*, it forces the brake mechanism to stop, resulting in the user experiencing the virtual environment as accurately compared to the real-world environment (Zhao, 2018).

Figure 5.4 Virtual trashcan (XR Access, 2021)

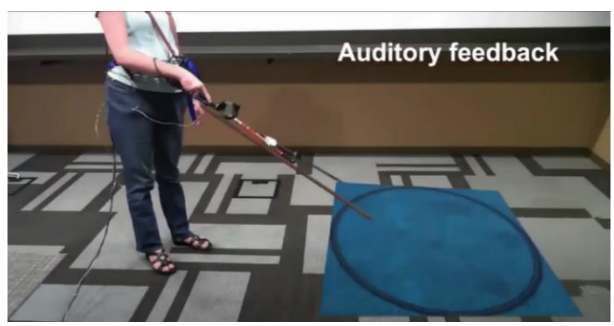


Figure 5.5 Virtual carpet (XR Access, 2021)

The voice coil creates vibrotactile feedback to stimulate vibrations people feel when they interact with different environments, either when the cane hits a different object or when it is swept on different surface textures, such as a carpet, smooth floor, or dotted tile.

Spatial auditory feedback also provides feedback when the cane interacts with the virtual environment. A set range of real-life audio recorded by Zhao and her team is played back to the user, creating the experience of similar sounds in virtual reality as in real life. For example, the spatial auditory feedback in *figure 5.4* would have been the sound of a plastic trashcan when the cane hits it, and *figure 5.5* would create the sound of a cane being swept on the carpet.

Results of the multimodal feedback

Combining these multimodal feedback elements, the three standard cane techniques can be supported: shorelining, constant contact, and two-point touch, resulting in virtual environment navigation being similar to the real-world experience.

Shorelining can be achieved by the brake mechanism stopping the *Canetroller* from moving further than the virtual wall, as shown in *figure 5.6.* In addition, providing the user with vibrations via the voice coil when hitting the wall and audio sounds for additional information.

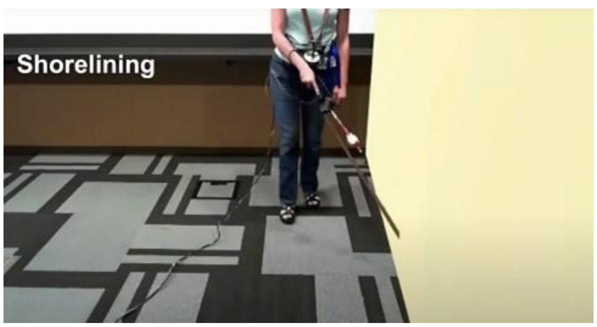


Figure 5.6 Shorelining (XR Access, 2021)

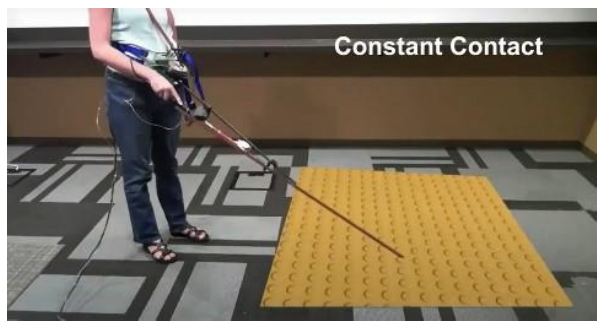


Figure 5.7 Constant contact (XR Access, 2021)

With **constant contact** and **two-point touch** being achievable, the vibrations and sound can help the user identify the virtual dotted tile in *figure 5.7*, an essential navigational tool for blind users in real life, indicating a road crossing or other possible dangerous situations (Zhao, 2018).

5.2.2 Zhao's Study of Canetroller

This section presents the study conducted to collect data after creating the *Canetroller*; by doing so, Zhao and her team can measure if the Canetroller was successful or not.

After successfully creating the *Canetroller*, which could provide the user with crucial feedback needed to experience virtual use of the cane similar to the use in the real world. Dr. Yuhang Zhao and her team further evaluated the *Canetroller* in different virtual scenes; one simulates an inside environment, and one simulates an outdoors environment (Zhao, 2018). The purpose of the evaluation was to find out how effective the *Canetroller* is when exploring different virtual reality scenes. And to gather qualitative data to see what visually impaired people's experiences with the *Canetroller* were. To conduct this evaluation, nine people with visual impairments were recruited (five females and four males. From age 25-to 63, avg. 39), all legally blind and white cane users in real life (Zhao, 2018).

The test procedure was to first introduce the users to the *Canetroller* by a tutorial session, where they could get comfortable and better understand the technology. Then, once the user felt comfortable and ready to start the test, they were placed in two different virtual environments, indoor and outdoor environments, with a specific task for each environment while exploring around (Zhao, 2018).

The indoor (*figure 5.9a)* environment is a closed room with four walls, a carpeted floor, a metal table, a plastic trashcan, and a wooden door. Their task was to freely explore the virtual environment and ask them to position themselves in what they thought was the middle of the room and provide information about how many objects were in the room, pointing out the general direction to where the virtual objects were found.

The outdoor (*figure 5.9b)* environment was a simulation of a street with traffic, with spatial audio to inform users of the direction of the traffic. The virtual environment had a street curb, a metal traffic light pole, and tactile dotted tiles to indicate where the user should cross the street. Their task was to explore the space, distinguish the traffic direction and try to cross the street.

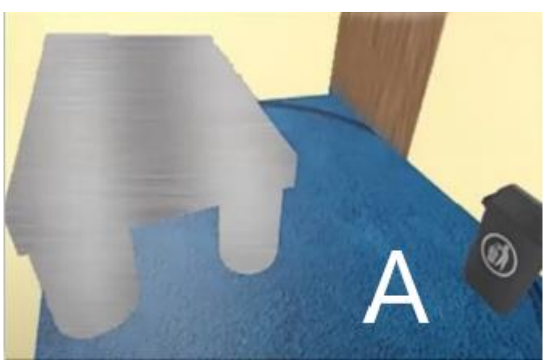


Figure 5.9a – Indoor environment (XR Access, 2021)

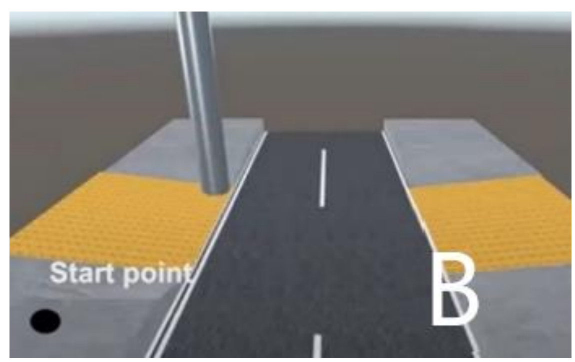


Figure 5.9b – Outdoor environment (XR Access, 2021)

After exploring both virtual scenes, users were presented with a presence questionnaire, with eight questions about how immersive the experience felt for them, with statements/questions like

"*In the virtual world, I had a sense of being there,*" and then were asked to give a score from 1-7 to interrogate an agreement with the stigma.

5.2.4 Zhao's Results of the Canetroller Study

This section presents the results gathered from conducting the studies where fully blind users tested the *Canetroller*. These results are significant as they prove the usability of the *Canetroller,* which further supports the possibility of creating a more accessible virtual reality for fully blind users. These studies can further value the importance of developing virtual reality for visually impaired people. If shown a positive outcome, it can provide the needed data for other developers to realize the possibilities and results of adding such a solution to their virtual reality.

Study result: The results gathered by Dr. Yuhang Zhao and her research team from the evaluation of visually impaired people using their *Canetroller* proved that the *Canetroller* was very effective for most of the participants. With 8 out of 9 participants successfully able to correctly locate all virtual objects in the indoor environment. And 6 out of 9 participants successfully crossed the street with minimum assistance from the research team. However, three participants had difficulties distinguishing the traffic sound because of their general limitation of understanding which way traffic was moving, resulting in difficulties in crossing the street: *confusion of the 3D audio.*

Sense of presence result: To better indicate the future of which environment should be simulated as a more immersive experience for people to explore with the *Canetroller*, the participants were asked to rate each environment on its immersion from 1 to 7. The average for the indoor environment was 5.3, while the average for the outdoor was 5.1 (Zhao, 2018). It resulted in no significant differences between the two environments.

Behaviors with *Canetroller*: All participants used real-world white cane techniques with the *Canetroller*, resulting in easy adaptation to the virtual world and could perceive the size and shape of the virtual objects, creating a good mental model and association of the object was.

> *"it's a big desk because I found two legs and then a while later, I found that third leg" – f (29)* (XR Access, 2021)

Dominant feedback: Participants were also asked which of the feedback generated by the *Canetroller* was most significant for them, with results of; **two** voting for physical resistance, **three** for audio feedback, and **four** for the combination of both. They implied that each feedback from the *Canetroller* had a significant impact on the users.

> "*[The physical resistance] was the way to create the boundaries between various virtual objects. When perceiving minor details, the sound cannot convey that. The force made it realistic." – m (25)* (XR Access, 2021)

Overall, the final result of the *Canetroller* was proven to be a possible technology solution for the visually impaired, especially blind users, in virtual reality, with possibilities to navigate and get an understanding of their surrounding virtual environment.

5.2.5 Summary of Canetroller

Canetroller is a concept developed by Dr.Yuhang Zhao et al. (2018), which is created to enable visually blind users to navigate the virtual reality environment using the Canetroller based on a real-life white cane. It allows users to use the same techniques and methods of navigating inside the virtual environment as they used in real life. Multiple components such as physical resistance, vibrotactile feedback, and spatial auditory feedback create the same feeling as a blind person would feel in real life. The Canetroller then allows the user to navigate virtual reality, a primarily designed technology for visually abled people. It also makes learning how to use a white cane for newly impaired people safer, as the methods can be taught inside virtual reality instead of in the real world, where it could be dangerous, for example, when learning how to cross a road.

5.3 SeeingVR

In this section, I will be presenting Dr. Yuhang Zhao's study of *SeeingVR*, in which I will be presenting the goal of this study, the formative research conducted by Zhao and her team before creating SeeingVR. I will briefly describe each of the tools in SeeingVR and how these tools address the problems I collected my data about. Lastly, I will go over Zhao's study of SeeingVR and the data collected from visually impaired people using SeeingVR.

In this research, Dr. Yuhang Zhao and her research team focus on the other important group of visually impaired people with low vision, who prefer and can still use their functional vision to an extent in multiple daily activities. Zhao's research tries to make virtual reality more accessible for the group with low vision impairment, as many of them find the tasks in virtual reality challenging to interact with. By creating a set of tools called *SeeingVR*, which can be implicated directly into the virtual reality to aid the visually impaired in interacting with the virtual environment (Zhao, 2019).

5.3.1 Zhao's Formative Study - Limitations for Low Vision Users

Zhao conducted a formative study to understand the challenges people with low vision experience with VR and recruited six low vision participants to observe their VR experience (Zhao, 2019). On one the applications presented for the low vision participants was an escape room, an application similar to many other applications/games that visually impaired players can find. *Figure 4.10* shows the escape room, an open-source room-escape game where users find clues under objects in a dark room. The participant's objective in the application is to explore the space, read the low contrast text, and pick up different objects to find clues, often having to flip the object to reveal hidden clues.

Figure 5.10 – VR Escape room (Zhao, 2019).

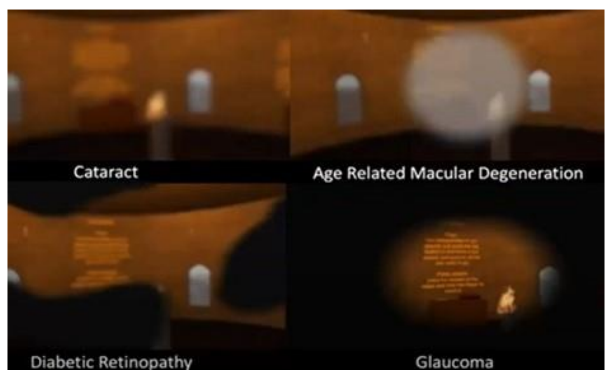


Figure 5.11 – VR Escape room – low vision (Zhao, 2019).

In terms of low vision conditions, there is much complexity. People often have multiple impairment conditions affecting their vision, making it difficult for visually impaired people to perceive all the complex and virtual environments. *Figure 4.11* displays some of the most common low vision conditions for visually impaired people. Interacting with virtual elements was a challenging task for participants; using a laser pointer to select a specific menu item could not distinguish where the laser pointer was aiming due to low contrast in the background and a thin line. Dealing with light effects in the escape room was also challenging, with the low contrast being a limitation for many participants (Zhao, 2019).

5.3.2 Vision Tools for Virtual Reality

In this section, I will be presenting the 14 tools that are created for SeeingVR, as these are important to address to showcase how they can resolve the problems for low-vision users of virtual reality. Furthermore, showcasing these solutions may also guide further development of accessibility tools for future virtual reality developers. Therefore, I will be addressing how these tools could become a solution for the problem collected through my data in the previous chapter.

Guided by the formative study conducted by Zhao and her research team, they designed SeeingVR, a set of 14 low vision tools that can augment a virtual reality application as an overlay with both visual and audio feedback *(figure 5.12)*. Users of SeeingVR can select, combine, and adjust different tools based on their preferences and needs in virtual reality (Zhao, 2019). With nine tools being able to argument VR applications without requiring the source code or any other type of developer effort to be implemented. The five remaining tools can be further augmented if the developers provide more metadata; the best example of this is object description, something developers would need to describe first before SeeingVR could take the information to use (Zhao, 2019).

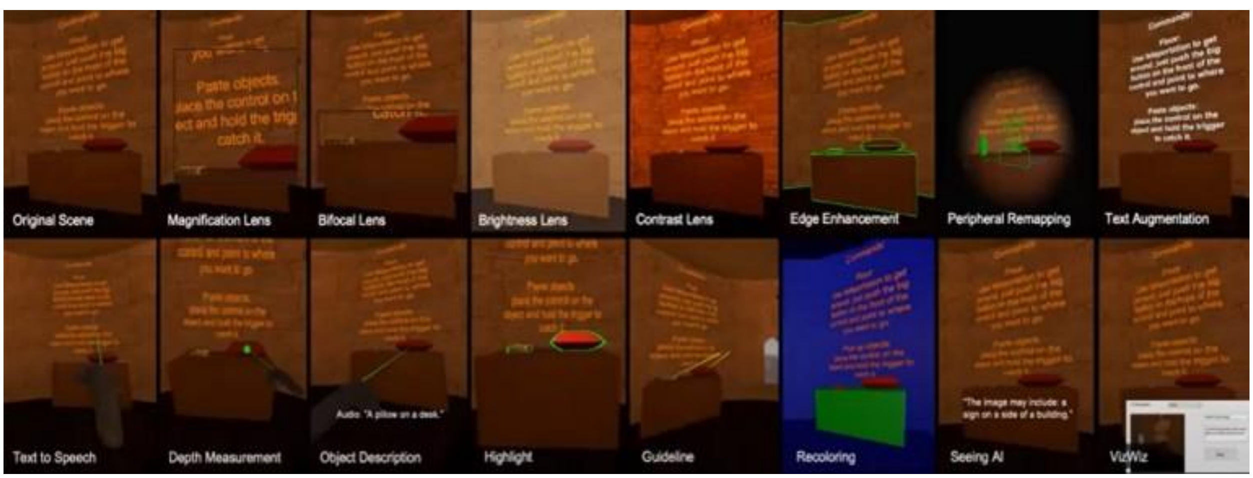


Figure 5.12 – "SeeingVR's 14 low vision tools (Zhao, 2019).

5.3.2.1 Description of 14 SeeingVR Tools

Zhao's design goal was to adapt the SeeingVR tools from the real-world low vision technologies and reduce the learning curve and cognitive load by adopting technologies already familiar to low vision people. Those are nine tools that are built-in "post hoc" plug that incorporates most of these tools directly into any existing Unity-based application. Furthermore, it modifies and augments these virtual scenes directly without needing any semantic information provided from the scene, meaning a user can install the tools and use them in the majority of Unity-based applications without any requirement of developer input.

The **Magnification Lens** creates a magnifying effect on the display, which helps low-vision users see details or objects far away (Zhao, 2019). As virtual reality often tends to have bigger environments, when objects or text may often be far away, the magnification lens helps the users with a lower vision to see those far away objects better. Looking back at the data collected from Survey B, 42 out of 82 respondents answered that they find “viewing things from a distance” difficult, indicating that the implications of a magnification lens could address this problem.

Figure 5.13 – Magnification Lens in SeeningVR (Zhao, 2019).

Bifocal Lens is a small rectangular-shaped magnifier to reduce the dramatic change that a magnifier brings. The bifocal lens is located at the bottom of the user’s visual field to allow the user to see the original virtual scene by looking through other areas of their visual field. The position of the lens can be adjusted higher or lower according to the position of the user’s functional vision (Zhao, 2019).

The **Bifocal Lens** is similar to the magnification lens; however, it is a small rectangular-shaped magnifier to reduce the dramatic change that a magnifier brings. (Zhao, 2019). Therefore, the bifocal lens can be placed towards the desired placement on the screen, for example, the bottom, resulting in a lens not covering the majority of the screen. This allows the user to use the lens, if need be, instead of constantly having the magnification on, creating a more realistic feel of the virtual environment. The bifocal lens is essential for the “inclusive design” which I mentioned in chapter two, which describes visual impairment in three different stages, permanent, temporary, and situational. Where the magnification tool is excellent for the permanent stage, the bifocal lens might be a better option for the temporary and/or situational stages, where the user might only need the tool of zooming in only a few times.

Contrast Lens helps increase the luminance contrast of virtual reality scenes, often resolving the problem of darker or doll contrast seen in virtual reality environments (Zhao, 2019). For example, in f*igure 5.13*, where the wall and text are a similar color, or the previously mentioned problem in chapter two, where the contrast in the interface was very low for the users. In addition, based on my data collected in chapter four, 30 respondents identified as color blind (the largest group in my survey), with additional 48 respondents struggling with “seeing color contrast” and 44 respondents struggling with “contrast” in general. This further proves that contrast is an issue in virtual reality, and solutions like the contrasting lens could address this issue, creating a more accessible virtual reality.

Edge Enhancement is specially added enhancement edges throughout the virtual environment that helps users with low vision to better distinguish different objects in a low contrast scene (Zhao, 2019). Based on my survey, one of the most inaccessible parts of virtual reality was “identifying different objects”, with 53 respondents finding that task difficult. Therefore, the edge enhancement can be a valuable tool to help users distinguish between different objects in the virtual environment.

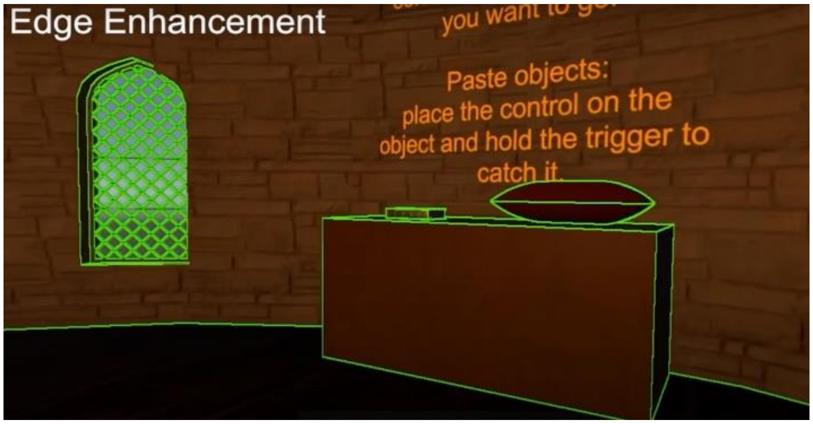


Figure 5.14 – Edge Enhancement in SeeingVR (Zhao, 2019).

Peripheral Remapping is designed for people with peripheral vision loss by overlaying the edges of the whole visual environment into the peripheral field of view (Zhao, 2019). Looking at *figure 5.15*, one can see the previously showcased edge enhancement taking place in the middle of the peripheral sight, giving the user a better picture of the environment around. This tool creates a more accessible virtual reality for visually impaired users, but it also introduces the option of combining different tools together to create the most accessible tools. It also inspires to further development by introducing a solution to a topic that perhaps could be challenging to address, as the developers might not often tackle peripheral vision.

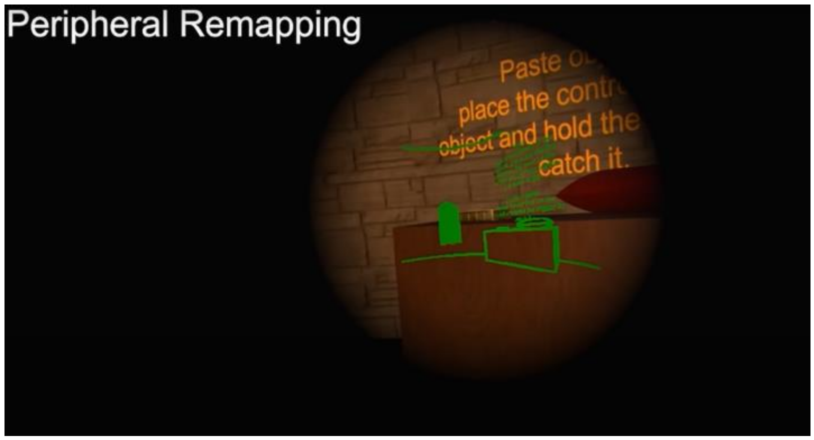


Figure 5.15 – Peripheral Remapping in SeeingVR (Zhao, 2019).

Text Augmentation automatically changes the text color to be inverted compared to the background; this allows for easier readability of the text, which often occurs by low contrast between the text itself and the background on which the text is placed. The text augmentation also allows the font size to be altered in size and boldness (Zhao, 2019). In my data collection from the survey, B presented in chapter five, "reading the content displayed on the screen" was answered as problematic by 45 out of 82 respondents, indicating that a tool such as text augmentation could provide a possible solution to this problem.

Text to Speech is created for scenarios where the visual augmentation is insufficient, with a text-to-speech tool providing audio augmentation. The text placed in the virtual environment will be read up when pointed at by the user (Zhao, 2019). In my data collection from Survey B, around 30 respondents found screen readers to be essential for them, further supporting the need for a text-to-speech tool. Especially for visually impaired users with significant limitations in reading text, a task difficult for many, as proven, is the previously mentioned text augmentation tool.

Depth Measurement is a tool for people with difficulties with depth perception, leading to limitations when picking up objects in a virtual reality environment. To address this problem, a laser attached to the virtual controller displays a ball when interacting with an object, resulting in the sense of depth for the user. In my collected data, 36 respondents found "pointing to select" inaccessible for them in virtual reality. This laser-ball solution could provide more accessibility for them and create depth measurement.

Figure 5.16 – Depth Measurement in SeeingVR (Zhao, 2019).

Those are the nine *post-hoc* tools that do not need developer input to work. Each of them addresses the different problems visually impaired users face and be limited by when using virtual reality. The remaining five additional tools can further enhance the virtual reality application by leveraging the developer's input; these five are:

Object Description is similar to how all text work with a screen reader used on a computer or mobile device. If a developer adds descriptions to objects in the virtual reality scene, the tool can read aloud the description if the user points to a labeled object (Zhao, 2019). This solution can address the most answered response to my data collection, where 53 respondents find "identifying different objects" inaccessible in virtual reality. By creating labels for each object, virtual reality can become more accessible for visually impaired people with the help of the object description that reads aloud the set labels.

Developers can use the highlight tool to showcase the object in the virtual environment. This highlight can indicate the object's placement, which otherwise could be hard to locate based on low contrast. Or the highlight tool can be used to display essential objects for the user (Zhao, 2019). Highlighting the object can also help identify it, as this task, as mentioned previously, is inaccessible for the majority of my respondents in survey B (53 out of 82 respondents) and the visual community in general.

Figure 5.17 – Highlight in SeeingVR (Zhao, 2019).

A **guideline** is a tool for creating lines connected to objects, helping users orientate and navigate to different objects that could be out of their field of view (Zhao, 2019). Developers can also implement the guideline specifically for important objects to help users navigate better (Zhao, 2019). Around 25 respondents of my survey showcased in the previous chapter find “sense of orientation” inaccessible. The guideline could address this problem by providing solutions that guide the users towards a chosen set of objects chosen by the developers.

Recoloring is a tool that changes the color based on the developer’s hierarchy of objects in the environment, resulting in recoloring the whole environment, creating a scene where every two objects close to each other in the user’s visual field are painted in different colors. This tool creates a more simple virtual environment for the users, as it takes away the complex textures, which can be confusing to the user, often blending together with the objects (Zhao, 2019). This could be a solution to the limitations found by users with color contrast problems and/or users with sight impairment to an extent where identifying objects is not necessarily done by the texture but by shape.

Zhao also mentions **Assistive Smartphone Apps** as a possibility of use in SeeingVR, in which the real-world application can be transferred into virtual reality. By introducing the popular assistive applications into SeeingVR, such as VizWiz, an application that recognizes and describes objects/scenes for visually impaired people could be implemented (Zhao, 2019. VizWiz, 2022). For example, the VizWiz application could allow a VR user to speak aloud a question, such as “What is in the image?” and the question with a screen capture of the virtual environment would be sent to a human. This could then provide the VR user answers that would be read aloud by the system.

5.3.4 Summary of the 14 SeeingVR tools

As showcased in this section, the 14 tools used in SeeingVR address some of the most impassible problems for visually impaired people in the current state of virtual reality. The SeeingVR can provide accessibility to the problems showcased in the previous chapters in this thesis, both in the literature and data collection chapter, answering the research question of the thesis. Firstly, the nine tools ready to go for every user provide the much saw after solutions, such as changing the color contrast and alternating the text wither by making it more visible or using a text to speech option. Or the object indication is done by outlining the virtual environment. Secondly, the five tools were created for the developers, allowing them to create a more accessible environment for their users by creating a set of labels and other features. How these are set will be showcased in the next section. The result of using the SeeingVR will also be showcased in this chapter. Finally, a section discussing Zhao’s study of the SeeingVR will be presented, indicating that the tools create a more accessible virtual environment for visually impaired users.

5.4 Unity Developer Toolkit

This section describes the Unity Developer Toolkit, where the virtual reality developers can implement the different tools mentioned in the previous section. By using the unity developer toolkit, virtual reality can become a more accessible technology for visually impaired people, as it implements settings created to make VR accessible. In addition, it also emphasizes user accessibility features for future developers of virtual reality.

Dr. Yuhang Zhao and her research team created and implemented the Unity toolkit for developers since five of their low vision tools the previously mentioned require developers to input semantic information. The developed Unity toolkit allows developers access to all 14 tools designed to make virtual reality more accessible for low vision users. For easier access and further development, Zhao additionally added a Unity prefab- a template with specific features, called “Accessibility Manager”. Which automatically adds all of the SeeingVR tools into the virtual reality app, which developers can also control after adding it (Zhao, 2019).

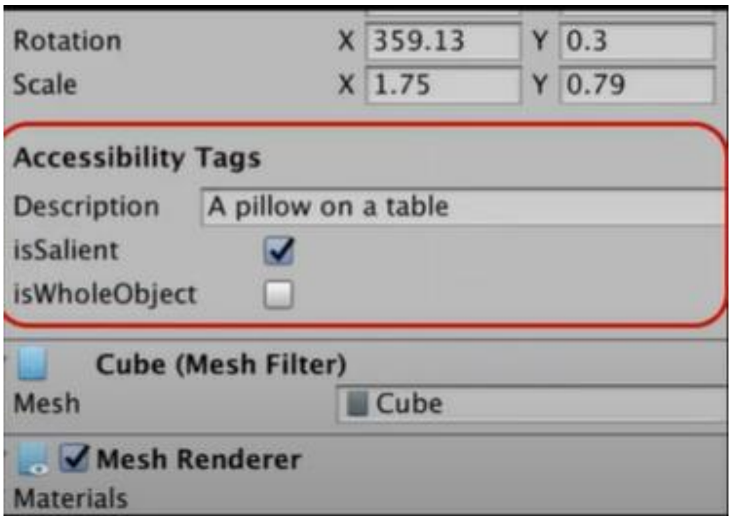


Figure 5.18 – The unity developer toolkit settings (Zhao, 2019).

One of the main features Zhao was hoping to accomplish by creating the Unity Developer Toolkit was for the developers to add descriptions, which would significantly increase the accessibility of virtual reality for low visions users. Simply adding a description of the object, as seen in *figure 4.26*, would create a more accessible environment, where each object could be read up aloud with the descriptions included (Zhao, 2019).

5.5 Zhao’s Study - SeeingVR

This section will present Zhao’s study of how visually impaired people use SeeingVR and how the unity developer toolkit is for the developers. The result of this study can provide data showcasing the usability and accessibility achieved by SeeingVR in virtual reality.

For this study, Zhao created two different groups, the first group of 11 low vision participants who were set to use the tools to conduct three different virtual tasks. For the second group, Zhao recruited six unity developers and asked them to use the toolkit and incorporate it into their developments, giving additional feedback at the end.

5.5.1 Study for Low Vision Users – Seeing VR

The 11 participants were presented with three significantly representative tasks in virtual reality: (1) menu navigation, (2) visual search for objects, and (3) target shooting *(Figure 4.27)*.

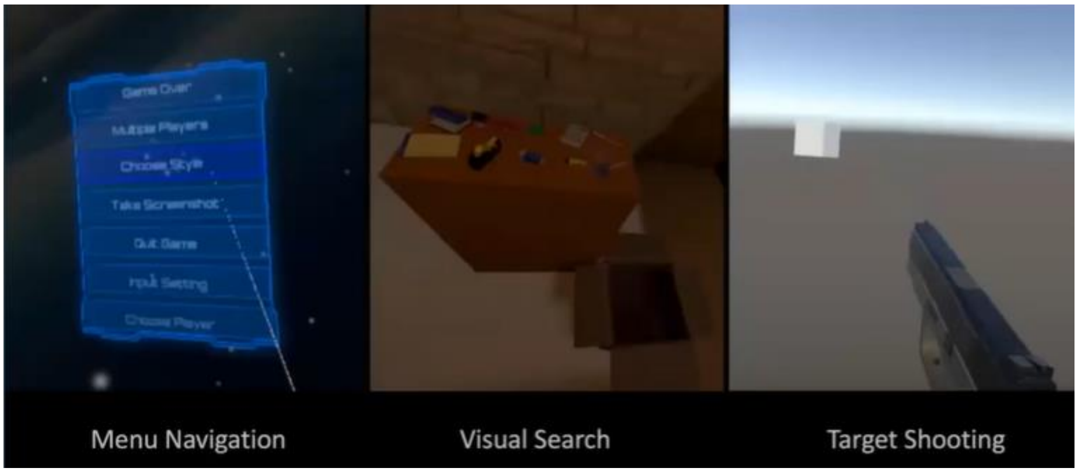


Figure 5.19 – Task given to users "menu navigation", "visual search" and "target shooting" (XR Access, 2021)

With visual impairment having different low vision conditions, each specific for every individual to an extent, the participants had a free choice of selecting their preferred tools to complete the given tasks, with their best correction time being without any tools, *best correction meaning if a participant needed glasses to see, it would be allowed* (Zhou, 2019).

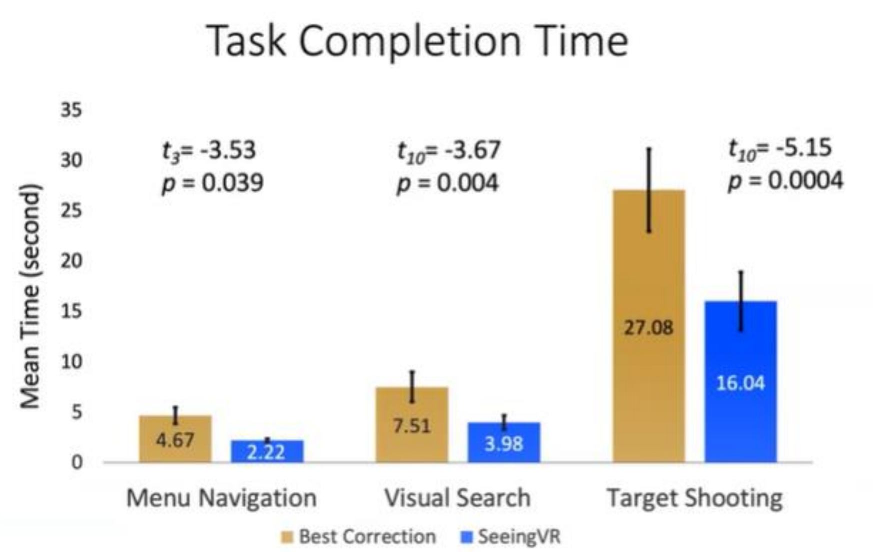


Figure 5.20 – Task completion time (XR Access, 2021)

5.5.2 Results of the study for low vision users:

The result of the study where low vision participants used the SeeingVR tools to better perceive different virtual environments with different virtual tasks shows data that confirms SeeingVR enhances the participant's performance in perceiving virtual reality through vision. The data shows the potential of SeeingVR significantly reducing the participant's time for completing a task, nearly decreasing the completion time by half of the time it took to complete the tasks without the use of SeeingVR (Zhou, 2019).

An additional response to the SeeingVR has been given to me from interviewing Jesse, also mentioned in the XR Access research seminar presented by Dr. Yuhang Zhao. Jesse is a legally blind VR user, with the most significant limitations regarding user accessibility in virtual menus. His limitations refer to the limited ability to move his head close enough to a virtual menu without it moving away – virtual menus often have a fixed distance, resulting in the movement away from the user when they get close. Other limitations include low contrast or small text size with limited text-to-speech options and an overall lack of user accessibility tools in virtual reality. Nevertheless, Jesse confirms that SeeingVR could provide the best virtual reality solution for visually impaired users ever created, with no other solution than the amount and usability of user accessibility tools provided through SeeingVR.

5.5.3 Zhao's Unity Developer Toolkit Study

To evaluate the opportunity of the Unity toolkit with developers, Zhao and her team recruited six unity developers to try out and incorporate the toolkit into their developments. The result of the study showed that all of the unit developers found the toolkit very easy to use and easy to incorporate into their ongoing projects. Zhao also mentioned that the developers even emphasized the importance of coming up with this type of solution to make virtual reality more accessible for visually impaired people (Zhou, 2019).

"*We sometimes got asked by (the) accessibility team (at our company), "You need to be accessible." But they don't really understand what accessibility is in the VR context. You are the first that actually look this deeply into this problem.*" – Developer (31, m) (Zhou, 2019).

5.6 Summary of Canetroller and SeeingVR

As visual impairment consists of multiple conditions, different solutions need to be created to provide the best accessibility for visually impaired people when using virtual reality technology. Dr. Yuhang Zhao accomplished this with her Microsoft research team. Together they created two different solutions to address specific conditions for visually impaired people: Canetroller for fully blind people and SeeingVR for people with low vision. The Canetroller creates a virtual white cane that can help blind people navigate the virtual environments, with positive feedback from the study conducted by Zhao. Furthermore, SeeingVR addresses a variety of low-vision problems in one specific plugin, providing users with 14 different tools, significantly improving the accessibility of virtual reality.

This two-research accomplished not only creating technology for a group of people limited by the lack of accessibility in virtual reality. It also showed how significant the problems are surrounding the visually impaired in virtual reality and how they can be addressed in the future. With virtual reality possibly developing into an everyday piece of technology for everyone, these solutions will become more essential to incorporate, making VR more accessible for visually impaired people.

Not only do both Zhao's and her team's inventions address the problems of inaccessibility for visually impaired people in virtual reality, presented in chapter two of the literature review, but these two innovations also further support my data collection. Each of the studies supports the needs of each visually impaired group, with Canetroller addressing the problems for fully blind users and SeeingVR addressing the problems for low-vision users. Both provide accessibility features that can be seen as significant improvements to the current state of virtual reality, resulting in a much more accessible virtual reality and a benchmark for further developments of new accessibility features.

5.7 Other Valuable Solutions

This section will emphasize critical disability theory as a solution for future improvement of virtual reality for visually impaired people.

As mentioned at the beginning of the paper, the critical disability theory underlines the lack of including visually impaired people in virtual reality development. The lack of visually impaired people in virtual reality development often results in user accessibility not being valued as importantly, as most developers are non-disabled people. A point that can be proven by looking at the current state of virtual reality, further supported throughout this thesis, is that there has not been enough focus on user accessibility development in the early stages of virtual reality.

By acknowledging the critical disability theory in terms of virtual reality, and thus the inclusion of visually impaired people in the development of future technologies can result in significant improvement. The developers can establish the critical user accessibility needs, which are often forgotten, as proven in this thesis by including visually impaired people. Including visually impaired people in virtual reality, development showcases the critical accessibility needs; it also saves time and money for the developers. The need to go back to the start to add user accessibility features gets significantly reduced by addressing the problems early in the development. A problem seen in the current state of virtual reality is where developers or people in need of user accessibility need to go back and add features or tools that could have been integrated from the start if only visually impaired people were included.

CHAPTER SIX: CONCLUSION

6.1 Introduction

Let us picture this; we live in the future; the year is 2030, and Meta has successfully achieved its goals of creating a virtual reality technology that is equally or even more used than computers and smartphones as we know them today. The concept of attending work meetings, school classes, and even concerts inside of a Metaverse using virtual reality has become a normality. However, throughout the eight years of development, the need for user accessibility in virtual reality has not been addressed enough for visually impaired people. Thus, visually impaired people are continued to be excluded from using this technology, resulting in the absence of social amenities. Visually impaired children can miss out on educational learning as metaverse classrooms become more used, which can also cause bullying within the children, where the visually abled may not understand why their visually impaired classmate struggles to use virtual reality. This can happen due to user accessibility for those visually impaired children, where problems mentioned in this thesis can occur. From struggling to identify different objects to not being able to read the displayed text in their virtual classroom as a result of accessibility lack.

Additionally, by not creating the metaverse accessible for visually impaired children, they might need to use older ways of learning while the other children use the metaverse, also resulting in exclusion. This is only one of many consequences that visually impaired people may face if user accessibility in virtual reality does not get fully addressed before mass development. Another example can be the opportunity for newly visually impaired people to use virtual reality to learn to cope with their new disability. Suddenly becoming visually impaired can be extremely hard for people, and learning a completely new way of living with that disability can be proven challenging. Therefore, as I showcased in the previous chapter by presenting Zhao's *Canetroller*, virtual reality can be used to teach visually impaired people to navigate a situation that might be difficult or dangerous for them in real life. Therefore, finding a solution that creates more accessibility for visually impaired people is crucial.

To address the current limitations of virtual reality for visually impaired people and answer the research question, this study aimed to create a problem-solution structure. The study begins by identifying the current problems and limitations that make virtual reality inaccessible for visually impaired people, emphasizing the difference in accessibility needs between low-vision and fully blind users. A data collection and analysis were conducted to further support the literature describing the problems, allowing for a more accurate description of the current problems. With the supported literature review, this study aimed to identify the importance of addressing the problems to create a more accessible experience for visually impaired people. Furthermore, by identifying the problem, the study presented possible solutions to help create a more accessible virtual reality. The possible solutions are not only addressing the current problems but also shining a spotlight on how future developers of virtual reality can address similar problems.

6.2 Limitations

The survey conducted for this thesis showcases the importance of the research. However, limiting factors could have granted me better results if eliminated. Firstly, the limiting factor of virtual reality not being accessible to visually impaired people limited the number of people that fit my criteria for the survey. In addition, the concept of virtual reality and especially metaverse is relatively new, resulting in a limited amount of people using it. While I am happy with the results of this study, I believe that more information and data could be gathered in several years as the use of virtual reality and metaverse becomes more popular by the public. However, as I aim to showcase throughout this thesis, the importance of addressing the problem of user accessibility needs to be addressed in the early stages of development; thus, even the number of answers I gathered can be helpful.

Furthermore, the concepts of *Canetroller* and *SeeingVR* created by Dr. Yuhang Zhao (Zhao, 2018, 2019) are not commercially available, limiting me down to only discussing them instead of enabling me a first-hand experience.

6.3 Future Research

This thesis is significantly targeting its research on the future of virtual reality for visually impaired people. The primary aim is to identify the current limitations so the future development of virtual reality can address these problems and create a more accessible and inclusive experience for the visually impaired. However, as the current research on this topic is only in the early stages, future research will be needed for the further and more specific identification of needed user accessibility features and tools for visually impaired people.

Specifically, continuing this research is important given the scope of Meta and other company's plans for virtual reality. Meta is planning to implement Metaverse as a significant method of socially interacting with other people; work meetings, school classrooms, and entertainment such as concerts and theaters could all occur in Metaverse. Not addressing the accessibility needs of visually impaired people will result in further limitations in their use of virtual reality. This can have consequences such as exclusion from participating in social gatherings, exclusion from some jobs previous accessible to the sigh impaired or even limited levels of learning in the education field. Therefore, future developers of Meta and other companies must acknowledge the need for user accessibility for visually impaired people.

Future researchers and developers of virtual reality also need to address the central tenants of critical disability theory by including visually impaired people in every step of development. Zhao's inclusion of visually impaired people in her development of *Canetroller* is a perfect example of how such research can be conducted, creating valuable results. By first acknowledging the problem and looking at ways the blind people use a white cane, then implementing it into the development of the Canetroller. Using the *Canetroller* as a case-study and development template would be an important way forward towards creating more accessible virtual spaces.

6.4 Summary

This thesis aimed to address the current problem with virtual reality for visually impaired people. A technology that is on the rise due to Meta's plans of using virtual reality as a new way of interacting with others, being able to join work meetings, school classrooms, and even concerts through virtual reality. However, the reviewed research and literature reveal that user accessibility in virtual reality is a problem for visually impaired people, resulting in the technology being significantly limiting or even unusable for many. To further support this statement and identify the problem, this thesis collected data from members of visually impaired communities. As a result of that data and literature review, I could establish the areas that needed further addressing, and identifying that the visually impaired can be divided into low-vision and fully blind. Each of these groups had its limitations and thus different ways of addressing the problem. This thesis provided possible solutions directed at both of these groups and how important user accessibility is for the visually impaired in general. As a result of this thesis, I have aimed to highlight the importance of addressing the current problem of virtual reality for visually impaired people. The result is a strong recommendation that the future development of virtual reality needs to include visually impaired people in their design and development. Along with continuing the development and implementation of the specific assistive technologies discussed in this thesis, these recommendations will result in virtual worlds which include sight impaired people and allows them to participate in these important and evolving technological advancements.

References

"About Age-Based Targeting". 2022. *Facebook*. https://www.facebook.com/business/help/103928676365132.

Andersson, R. L. 1993. "A Real Experiment In Virtual Environments: A Virtual Batting Cage". *Presence: Teleoperators And Virtual Environments* 2 (1): 16-33. doi:10.1162/pres.1993.2.1.16.

Armstrong, L. Helen. 2009. "Advanced IT Education For The Vision Impaired Via E-Learning". *Journal Of Information Technology Education: Research* 8: 243-256. doi:10.28945/691.

Bardi, Joe. 2022. "Virtual Reality Defined & Use Cases | 3D Cloud By Marxent". *3D Cloud™ By Marxent*. https://www.marxentlabs.com/what-is-virtual-reality/.

Bauer, Corinna M., Gabriella V. Hirsch, Lauren Zajac, Bang-Bon Koo, Olivier Collignon, and Lotfi B. Merabet. 2017. "Multimodal MR-Imaging Reveals Large-Scale Structural And Functional Connectivity Changes In Profound Early Blindness". *PLOS ONE* 12 (3): e0173064. doi:10.1371/journal.pone.0173064.

Beat Saber. 2020. *Twitter.Com*. https://twitter.com/beatsaber/status/1253333307812491267.

"Bio — John W. Creswell". 2022. *John W. Creswell*. https://www.johnwcreswell.com/bio.

Bishop, Gary, and Henry Fuchs. 1992. "Research Directions In Virtual Environments". *ACM SIGGRAPH Computer Graphics* 26 (3): 153-177. doi:10.1145/142413.142416.

Bowman, Doug A., and Ryan P. McMahan. 2007. "Virtual Reality: How Much Immersion Is Enough?". *Computer* 40 (7): 36-43. doi:10.1109/mc.2007.257.

"Building The Metaverse Responsibly | Meta". 2022. *Meta*. https://about.fb.com/news/2021/09/building-the-metaverse-responsibly/.

Burdea, Grigore, and Philippe Coiffet. 2003. "Virtual Reality Technology". *Presence: Teleoperators And Virtual Environments* 12 (6): 663-664. doi:10.1162/105474603322955950.

Burdea, Grigore, Paul Richard, and Philippe Coiffet. 1996. "Multimodal Virtual Reality: Input-Output Devices, System Integration, And Human Factors". *International Journal Of Human-Computer Interaction* 8 (1): 5-24. doi:10.1080/10447319609526138.

Castelvecchi, Davide. 2016. "Low-Cost Headsets Boost Virtual Reality’S Lab Appeal". *Nature* 533 (7602): 153-154. doi:10.1038/533153a.

Clarkson, P.John, Roger Coleman, Simeon Keates, and Cherie Lebbon. 2013. *Inclusive Design*.

Creswell, John. 2012. *Educational Research: Planning, Conducting, And Evaluating Quantitative And Qualitative Research*. 4th ed. Boston: Mass: Pearson.

Creswell, John. 2014. *Research Design: Qualitative, Quantitative And Mixed Methods Approaches*. 4th ed. Thousand Oaks: CA: Sage.

"Color Blindness I Clinton Eye Associates". 2022. *Clintoneye.Com*. Accessed May 17. https://www.clintoneye.com/color-blindness.html.

Deemer, Ashley D., Christopher K. Bradley, Nicole C. Ross, Danielle M. Natale, Rath Itthipanichpong, Frank S. Werblin, and Robert W. Massof. 2018. "Low Vision Enhancement With Head-Mounted Video Display Systems: Are We There Yet?". *Optometry And Vision Science* 95 (9): 694-703. doi:10.1097/opx.0000000000001278.

"Deuteranopia – Red-Green Color Blindness – Colblindor". 2022. *Color-Blindness.Com*. https://www.color-blindness.com/deuteranopia-red-green-color-blindness/.

"Designing Accessible VR Experiences". 2020. *Youtube.Com*. https://www.youtube.com/watch?v=yFVPMYDO_OE&ab_channel=MetaQuest.

"Does VR Have An Accessibility Problem? | Dr. Mar Gonzalez-Franco - XR Access". 2022. *XR Access*. https://xraccess.org/vr-accessibility-problem-mar-gonzalez-franco/.

Earnshaw, Rae A, M. A Gigante, and H Jones. 1993. *Virtual Reality Systems*. London: Academic Press.

Ebert, Christof. 2015. "Looking Into The Future". *IEEE Software* 32 (6): 92-97. doi:10.1109/ms.2015.142.

"Everything You Need To Know About White Canes". 2022. *The Lighthouse For The Blind, Inc.*. https://lhblind.org/everything-you-need-to-know-about-white-canes/.

"Eye Care, Vision Impairment And Blindness". 2022. *Who.Int*. https://www.who.int/health-topics/blindness-and-vision-loss#tab=tab_1.

"Facebook Buying Oculus Virtual-Reality Company For $2 Billion". 2014. *Time*. https://time.com/37842/facebook-oculus-rift/.

"Factsheet On Persons With Disabilities | United Nations Enable". 2022. *Un.Org*. https://www.un.org/development/desa/disabilities/resources/factsheet-on-persons-with-disabilities.html?fbclid=IwAR3OaIXYHVnPkBIAfYT_d0_D3p_vr1St4HlKWJoZVNBAZLwiq4orw_ezXik.

Fenrich, Peter. 2005. "What Can You Do To Virtually Teach Hands-On Skills?". *Issues In Informing Science And Information Technology* 2: 347-354. doi:10.28945/833.

Feltham, Jamie, David Heaney, and Harry Baker. 2022. "Carmack: Quest 'By Far Our Most Retentive Hardware', Rift S Surpasses Rift". *Uploadvr*. https://uploadvr.com/oculus-quest-rift-s-retention/.

"Forside". 2022. *Blindeforbundet*. https://www.blindeforbundet.no/.

Gerber, Elaine. 2003. "The Benefits Of And Barriers To Computer Use For Individuals Who Are Visually Impaired". *Journal Of Visual Impairment &Amp; Blindness* 97 (9): 536-550. doi:10.1177/0145482x0309700905.

Gonzalez-Franco, Dr.Mar. 2022. *Twitter*. https://twitter.com/twi_mar/status/1485828723492352002.

Goradia, Ishan, Jheel Doshi, and Lakshmi Kurup. 2022. "A Review Paper On Oculus Rift & Project Morpheus". *International Journal Of Current Engineering And Technology*.

Hagen, Rebecca, and Kim Golombisky. 2016. *White Space Is Not Your Enemy*. 3rd ed. A K Peters/CRC Press.

Haider, Shamanta. 2022. "The State Of Disability — Accesscan". *Accesscan*. https://www.access-can.ca/news/the-state-of-disability.

Harper, Simon, Carole Goble, and Robert Stevens. 2000. "A Pilot Study To Examine The Mobility Problems Of Visually Impaired Users Travelling The Web". *ACM SIGCAPH Computers And The Physically Handicapped*, 30-41.

"Home | XR Access Initiative". 2022. *XR Access*. https://xraccess.org/.

"Illegallysighted". 2022. *Youtube*. https://www.youtube.com/user/IllegallySighted.

"Is The Metaverse The Solution For The Modern Office?". 2022. *T3*. https://www.t3.com/news/is-the-metaverse-the-solution-for-the-modern-office.

James, Paul. 2022. "Oculus To Debut Rift Developer Kit 2 Next Month At GDC 2014? – Road To VR". *Road To VR*. https://www.roadtovr.com/oculus-plan-debut-developer-kit-2-gdc-2014/.

Jensen, Christine, and Christine Jensen. 2018. "Kunsten Å Lese Med Ører Og Fingre". *Nrkbeta*. https://nrkbeta.no/2018/06/03/kunsten-a-lese-med-orer-og-fingre/.

Krekling, Elise Dees, Lene A. Hagen, and Rigmor C. Baraas. 2018. "Fargesynssvakheter Bør Avdekkes I Ung Alder". *Tidsskriftet.No*. https://tidsskriftet.no/2018/08/kommentar/fargesynssvakheter-bor-avdekkes-i-ung-alder.

Lan Li, Qing Jiang. 2022. "Application Of Virtual Reality Technology In Clinical Medicine". *Pubmed Central (PMC)*. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5622235/.

Lang, Ben. 2013. "What Does It Look Like In The Oculus Rift? - Road To VR". *Road To VR*. https://www.roadtovr.com/what-does-it-look-like-in-the-oculus-rift/.

Lium, Kristoffer. 2022. “User accessibility for visually impaired in virtual reality“ Interview by Milosz Zygmunt Waskiewicz. Via Zoom.

Meekosha, Helen, and Russell Shuttleworth. 2009. "What's So ‘Critical’ About Critical Disability Studies?". *Australian Journal Of Human Rights* 15 (1): 47-75. doi:10.1080/1323238x.2009.11910861.

Mereu, Stephen W., and Rick Kazman. 1997. "Audio Enhanced 3D Interfaces For Visually Impaired Users". *ACM SIGCAPH Computers And The Physically Handicapped*, no. 57: 10-15. doi:10.1145/250025.250029.

Mott, Martez, Edward Cutrell, Mar Gonzalez Franco, Christian Holz, Eyal Ofek, Richard Stoakley, and Meredith Ringel Morris. 2019. "Accessible By Design: An Opportunity For Virtual Reality". *2019 IEEE International Symposium On Mixed And Augmented Reality Adjunct (ISMAR-Adjunct)*. doi:10.1109/ismar-adjunct.2019.00122.

Murphy, Mike. 2022. "Facebook Has A Lesson To Learn From Nintendo’S Massive 1990S Virtual Reality Failure". *Quartz*. https://qz.com/649337/the-last-time-a-massively-hyped-vr-console-launched-in-the-us-was-in-1995-and-it-completely-flopped/.

"Muse Announce New VR Concert Experience 'Enter The Simulation'". 2022. *NME*. https://www.nme.com/news/music/muse-announce-new-vr-concert-experience-enter-the-simulation-3050133.

"Oculus Rift DK1: Full Specification - Vrcompare". 2022. *Vrcompare*. https://vr-compare.com/headset/oculusriftdk1.

"Oculus Rift DK1: Full Specification - Vrcompare". 2022. *Vrcompare*. https://vr-compare.com/headset/oculusriftdk1.

"Oculus Rift: Step Into The Game". 2022. *Kickstarter*. https://www.kickstarter.com/projects/1523379957/oculus-rift-step-into-the-game.

O'Malley, Marcia Kilchenman. 2008. "HCI Beyond The GUI Design For Haptic, Speech, Olfactory, And Other Nontraditional Interfaces", 25-73.

Roetenberg, D, H. Luinge, and P. Slycke. 2009. "Xsens MVN: Full 6DOF Human Motion Tracking Using Miniature Inertial Sensors". *Xsens Motion Technologies BV, Tech.*.

Rubin, H.J., and I.S. Rubin. 2005. *Qualitative Interviewing: The Art Of Hearing The Data*. 2nd ed. Thousand Oaks, CA.

Rogerson, James. 2021. "Mobile VR - What Smartphones Work With Virtual Reality?". *3G.Co.Uk*. https://3g.co.uk/guides/what-smartphones-work-with-virtual-reality.

Saber, Beat. 2019. "Beat Saber On Steam". *Store.Steampowered.Com*. https://store.steampowered.com/app/620980/Beat_Saber/.

Schultheis, Maria T., and Albert A. Rizzo. 2001. "The Application Of Virtual Reality Technology In Rehabilitation.". *Rehabilitation Psychology* 46 (3): 296-311. doi:10.1037/0090-5550.46.3.296.

Sutherland, Ivan E. 1965. *The Ultimate Display*. Proceedings of IFIP Congress 2.

Sutherland, Ivan E. 1968. "A Head-Mounted Three Dimensional Display". *Proceedings Of The December 9-11, 1968, Fall Joint Computer Conference, Part I On - AFIPS '68 (Fall, Part I)*. doi:10.1145/1476589.1476686.

Sveistrup, Heidi. 2004. *Journal Of Neuroengineering And Rehabilitation* 1 (1): 10. doi:10.1186/1743-0003-1-10.

Technologies, Unity. 2022. "Virtual Reality". *Unity*. https://unity.com/unity/features/vr.

"The Pandemic Was Great For Zoom. What Happens When There'S A Vaccine?". 2022. *Vox*. https://www.vox.com/recode/21726260/zoom-microsoft-teams-video-conferencing-post-pandemic-coronavirus.

Thomas, Rachel, Lucy Barker, Gary Rubin, and Annegret Dahlmann-Noor. 2015. "Assistive Technology For Children And Young People With Low Vision". *Cochrane Database Of Systematic Reviews*. doi:10.1002/14651858.cd011350.pub2.

Thompson, Tim. 2007. "Diane Pothier And Richard Devlin, Eds. Critical Disability Theory: Essays In Philosophy, Politics, And Law.". *Disability Studies Quarterly* 27 (4). doi:10.18061/dsq.v27i4.59.

"Top 10 Leading Virtual Reality Companies In 2017 | Veer VR Blog". 2022. *Veer.Tv*. https://veer.tv/blog/top-10-leading-virtual-reality-companies-in-2017/.

"Virtual Reality - Education And Training". 2022. *Encyclopedia Britannica*. https://www.britannica.com/technology/virtual-reality/Education-and-training#ref884324.

"Vision Impairment". 2022. *Raising Children Network*. https://raisingchildren.net.au/disability/guide-to-disabilities/assessment-diagnosis/vision-impairment.

"Vision Impairment And Blindness". 2022. *Who.Int*. https://www.who.int/news-room/fact-sheets/detail/blindness-and-visual-impairment.

"Visual Impairment (For Teens) - Nemours Kidshealth". 2022. *Kidshealth.Org*. https://kidshealth.org/en/teens/visual-impairment.html.

"Vizwiz – Algorithms To Assist People Who Are Blind". 2022. *Vizwiz.Org*. Accessed May 17. https://vizwiz.org/.

VR, Oculus. 2022. "Evolving From Oculus For Business To Quest For Business". *Developer.Oculus.Com*. https://developer.oculus.com/blog/evolving-from-oculus-for-business-to-quest-for-business/.

Waskiewicz, Milosz. 2022. “Interview” *Virtual Reality for the Visually Impaired*, via Zoom.

(WAI), W3C. 2022. "Accessibility, Usability, And Inclusion". *Web Accessibility Initiative (WAI)*. https://www.w3.org/WAI/fundamentals/accessibility-usability-inclusion/.

Wobbrock, J.O, K.Z Gajos, S.K Kane, and G.C Vanderheiden. 2018. *Ability-Based Design. Communications Of The ACM*.

Wood, Tyriel. 2020. "Oculus Quest 2 - The Software Tour! & Privacy Options". *Youtube.Com*. https://www.youtube.com/watch?v=ScPz-8iUEOg&ab_channel=TyrielWood-VRTech.

"Working From Home? 12 Challenges And How To Overcome Them". 2022. *Betterup.Com*. https://www.betterup.com/blog/challenges-of-working-from-home.

You, S., and U. Neumann. 2001. "Fusion Of Vision And Gyro Tracking For Robust Augmented Reality Registration". *Proceedings IEEE Virtual Reality 2001*. doi:10.1109/vr.2001.913772.

Zhao, Yuhang. 2022. "Designing Technologies To Make Virtual Reality Accessible For People With Visual Impairments | Dr. Yuhang Zhao - XR Access". *XR Access*. https://xraccess.org/xr-access-research-seminar-dr-yuhang-zhao/.

Zhao, Yuhang, Cynthia L. Bennett, Hrvoje Benko, Edward Cutrell, Christian Holz, Meredith Morris, and Mike Sinclair. 2018. "Enabling People With Visual Impairments To Navigate Virtual Reality With A Haptic And Auditory Cane Simulation". *Cs.Stanford.Edu.*.

Zhao, Yuhang, Edward Cutrell, Christian Holz, Meredith Morris, Eyal Ofek, and Andrew D. Wilson. 2019. "SeeingVR: A Set Of Tools To Make Virtual Reality More Accessible To People With Low Vision". *Microsoft.Com*. https://www.microsoft.com/en-us/research/uploads/prod/2019/01/SeeingVRchi2019.pdf.

Zhao, Yuhang. 2017. "Understanding Low Vision People'S Visual Perception On Commercial Augmented Reality Glasses". *Proceedings Of The 2017 CHI Conference On Human Factors In Computing Systems*, 4170–4181.

Table of Figures

Survey B Appendix and Complete Dataset

The following pages of this paper include a complete set of questions presented in survey B, and the complete data set collected from these questions.

Does VR have a user accessibility problem for the visually impaired?

- No personal information such as names or email addresses will not be collected, nor shared or used in any way in this survey. Your identity will stay anonymous and the collected data will only be used for the purpose of my thesis. -

Hi, and thank you for your time!
My name is Milosz, and I am a master's thesis student at the University of Bergen, studying user accessibility in virtual reality for visually impaired users.

Virtual reality (VR) has developed a massive spike in popularity in the last decade, with Facebook currently focusing more on VR as a tool for work and school-related activities.

The survey aims to identify which areas lack the accessibility for visually impaired users and create an overview of accessibility features, which developers could then implement in VRs technology to create a more inclusive tech for visually impaired users.

For any questions regarding the survey, please get in touch with me at Milosz.Waskiewicz@student.uib.no, or comment my post where you found the link.

Thank you for taking the time to answer the following question.

---

*Må fylles ut

1. To which gender do you identify most? *

Markér bare én oval.

- Male
- Female
- Non-Binary
- Other

2. What is your age? *

Markér bare én oval.

- 12-17
- 18-24
- 25-34
- 35-44
- 45-54
- 55+

3. What type of visual impairment describes your vision loss? *

Merk av for alt som passer

- [ ] Loss of Central Vision
- [ ] Loss of Peripheral (Side) Vision
- [ ] Blurred Vision
- [ ] Generalized Haze
- [ ] Extreme Light Sensitivity
- [ ] Night Blindness
- [ ] Vision Loss in One Eye
- [ ] Fully Blind
- [ ] I am not visually impaired
- [ ] Color blind
- [ ] Andre: ______________________

4. How often have you used virtual reality (VR) before? *

Markér bare én oval.

- ( ) 0 times
- ( ) 1-2 times
- ( ) 3-6 times
- ( ) 6-10 times
- ( ) 10 + times

5. How challenging would you describe your overall experience with virtual reality (VR)? *

Markér bare én oval.

- ( ) Very challenging
- ( ) Challenging
- ( ) Neither challenging or easy
- ( ) Easy
- ( ) Very easy

*

6. Which of the points below do you find inaccessible while using virtual reality (VR)? You can select multiple answers.

Merk av for alt som passer

- ☐ Setting up/connecting the virtual reality (VR) system
- ☐ User interfaces
- ☐ Moving around
- ☐ Reading the content displayed on the screen
- ☐ Identifying different objects
- ☐ Seeing the color contrast
- ☐ Contrast
- ☐ Pointing to select
- ☐ Spatial audio feedback
- ☐ Sense of orientation
- ☐ Haptic feedback (vibration when touching something)
- ☐ Viewing things up close Viewing
- ☐ things from a distance Andre:
- ☐ ______________________

7. On a scale from 0 to 10: How essential is a screen reader for your ability to* read the displayed text? 0 being not essential, 10 being significantly essential.

Markér bare én oval.

	0	1	2	3	4	5	6	7	8	9	10	
Not essential	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	Significantly essential

8. On a scale from 0 to 10: How essential are sound-location cues for you? 0 * being not essential, 10 being significantly essential.

Markér bare én oval.

	0	1	2	3	4	5	6	7	8	9	10	
Not essential	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	Significantly essential

9. On a scale from 0 to 10: How essential is haptic feedback for you? 0 being * not essential, 10 being significantly essential.

Markér bare én oval.

*

	0	1	2	3	4	5	6	7	8	9	10	
Not essential												Significantly essential

10. If you had to choose the MOST practical virtual reality (VR) feature for you, which one would it be?

Markér bare én oval.

- Spatial audio
- Haptic feedback
- Description of objects and surroundings
- Movement and motion tracking
- The immersion into the virtual world
- Vision aid programs (Text to speech, zoom in)
- The ability to communicate with others
- Color and contrast enhancement Andre:
- ________________________

11. If you had to choose the LEAST practical virtual reality (VR) feature for you, which one would it be? *

Markér bare én oval.

- Spatial audio
- Haptic feedback
- Description of objects and surroundings
- Movement and motion tracking
- The immersion into the virtual world
- Vision aid programs (Text to speech, zoom in)
- The ability to communicate with others
- Color and contrast enhancement Andre:
- ________________________

*

12. On a scale from 0 to 10: Based on VRs current state of development, how * willing would you be to use virtual reality (VR) for work or school-related meetings? 0 being very unwilling, 10 being highly willing.

Markér bare én oval.

13. Overall, would you say that virtual reality has an accessibility problem limiting its potential for visually impaired users?

Markér bare én oval.

- Yes
- Maybe
- No

1. To which gender do you identify most?	2. What is your age?	3. What type of visual impairment describes your vision loss?	4. How often have you used virtual reality (VR) before?
Male	25-34	Blurred Vision	10 + times
Male	18-24	Blurred Vision, Generalized Haze, Extreme Light Sensitivity, Color blind	6-10 times
Male	25-34	Generalized Haze, Extreme Light Sensitivity, Night Blindness, Vision Loss in One Eye	6-10 times
Male	25-34	Fully Blind	10 + times
Male	25-34	Loss of Central Vision	10 + times
Male	25-34	Loss of Central Vision, Blurred Vision, Extreme Light Sensitivity, Night Blindness	10 + times
Male	25-34	Loss of Peripheral (Side) Vision, Blurred Vision	6-10 times
Male	18-24	Fully Blind	1-2 times
Male	45-54	Loss of peripheral vision, night blindness, extreme light sensitivity, and everything is just darker now than it used to be.	10 + times
Female	25-34	Blurred Vision, Vision Loss in One Eye	3-6 times
Female	18-24	Fully Blind	1-2 times
Male	18-24	Extreme Light Sensitivity, Night Blindness, Color blind	6-10 times
Male	25-34	Fully Blind	10 + times
Male	25-34	Loss of Central Vision, Loss of Peripheral (Side) Vision, Blurred Vision, Generalized Haze, Extreme Light Sensitivity, Night Blindness, Vision Loss in One Eye	6-10 times
Female	25-34	Blurred Vision	1-2 times
Male	18-24	Color blind	3-6 times
Male	25-34	Fully Blind	3-6 times
Female	25-34	Loss of Central Vision, Blurred Vision, Generalized Haze, Color blind	3-6 times
Male	25-34	Loss of Central Vision	10 + times
Male	25-34	Fully Blind	1-2 times
Male	25-34	Fully Blind	1-2 times
Male	18-24	Color blind	10 + times
Male	25-34	Loss of Central Vision, Loss of Peripheral (Side) Vision, Blurred Vision, Generalized Haze, Extreme Light Sensitivity, Night Blindness	10 + times
Male	35-44	Fully Blind	3-6 times
Male	25-34	Fully Blind	3-6 times
Male	25-34	Blurred Vision, Vision Loss in One Eye	3-6 times
Male	18-24	Fully Blind	3-6 times
Female	18-24	Loss of Central Vision, Color blind	1-2 times
Male	18-24	Loss of Peripheral (Side) Vision, Blurred Vision, Extreme Light Sensitivity, Night Blindness	3-6 times
Female	18-24	Fully Blind	1-2 times
Male	18-24	Vision Loss in One Eye	3-6 times
Male	18-24	Blurred Vision	10 + times
Male	18-24	Color blind	10 + times
Male	18-24	Blurred Vision	6-10 times
Male	18-24	Loss of Peripheral (Side) Vision	3-6 times
Male	18-24	Blurred Vision, Color blind	6-10 times
Male	25-34	Blurred Vision	1-2 times
Male	25-34	Loss of Central Vision, Blurred Vision, Extreme Light Sensitivity, Color blind	6-10 times
Female	18-24	Color blind	1-2 times
Male	45-54	Color blind	10 + times
Male	18-24	Loss of Central Vision, Blurred Vision	1-2 times
Male	35-44	Color blind	6-10 times
Male	18-24	Loss of Central Vision	6-10 times
Male	18-24	Fully Blind	3-6 times
Male	25-34	Loss of Peripheral (Side) Vision, Blurred Vision, Extreme Light Sensitivity, Color blind	6-10 times
Male	25-34	Blurred Vision	10 + times
Non-Binary	18-24	Fully Blind	1-2 times
Male	25-34	Loss of Central Vision, Loss of Peripheral (Side) Vision, Blurred Vision	1-2 times
Male	18-24	Blurred Vision, Color blind	6-10 times
Male	18-24	Color blind	10 + times
Male	25-34	Color blind	6-10 times
Male	25-34	Blurred Vision	6-10 times
Male	18-24	Fully Blind	1-2 times
Non-Binary	35-44	Loss of Peripheral (Side) Vision	3-6 times
Male	35-44	Blurred Vision, Generalized Haze, Extreme Light Sensitivity, Night Blindness	6-10 times
Male	25-34	Blurred Vision	1-2 times
Male	25-34	Color blind	10 + times
Male	18-24	Color blind	10 + times
Female	25-34	I am not visually impaired	1-2 times
Female	25-34	Loss of Central Vision	6-10 times
Male	45-54	Color blind	3-6 times
Male	25-34	Blurred vision and sight loss	6-10 times
Male	25-34	Blurred Vision	10 + times
Male	18-24	Blurred Vision	3-6 times
Female	18-24	Color blind	6-10 times
Male	25-34	Color blind	10 + times
Male	18-24	Only slight light sensitivity	10 + times
Male	25-34	Vision Loss in One Eye	10 + times
Male	25-34	Blurred Vision, Color blind	10 + times
Female	18-24	Color blind	10 + times
Male	35-44	Color blind	3-6 times
Male	25-34	Extreme Light Sensitivity	10 + times
Female	25-34	Color blind	10 + times
Male	25-34	Loss of Central Vision	3-6 times
Male	18-24	Color blind	10 + times
Non-Binary	18-24	Blurred Vision	10 + times
Male	35-44	a mix of everything above unfortunately, plus deuteranopia (partial color blindness affecting the light green/yellow part of the light spectrum)	10 + times
Male	18-24	Color blind	10 + times
Male	18-24	Color blind	10 + times
Male	25-34	Color blind	10 + times
Male	25-34	I am not visually impaired	10 + times
Male	12-17	Color blind	10 + times

5. How challenging would you describe your overall experience with virtual reality (VR)?
Challenging
Challenging
Challenging
Challenging
Challenging
Challenging
Challenging
Very challenging
Very challenging
Challenging
Very challenging
Challenging
Challenging
Challenging
Very easy
Challenging
Challenging
Very challenging
Challenging
Very challenging
Very challenging
Easy
Challenging
Very challenging
Very challenging
Challenging
Very challenging
Very challenging
Very challenging
Very challenging
Challenging
Challenging
Neither challenging or easy
Challenging
Challenging
Very challenging
Challenging
Challenging
Easy
Neither challenging or easy
Easy
Challenging
Challenging
Very challenging
Very challenging
Easy
Very challenging
Challenging
Challenging
Challenging
Challenging
Challenging
Very challenging
Challenging
Challenging
Challenging
Challenging
Challenging
Easy
Challenging
Neither challenging or easy
Challenging
Easy
Challenging
Easy
Easy
Easy
Easy
Challenging
Challenging
Neither challenging or easy
Very easy
Easy
Challenging
Neither challenging or easy
Challenging
Very easy
Easy
Easy
Neither challenging or easy
Easy
Neither challenging or easy

6. Which of the points below do you find inaccessible while using virtual reality (VR)? You can select multiple answers.
User interfaces, Reading the content displayed on the screen, Identifying different objects, Seeing the color contrast, Contrast, Viewing things up close, Viewing things from a distance
User interfaces, Identifying different objects, Seeing the color contrast, Contrast, Viewing things from a distance
Identifying different objects, Seeing the color contrast, Contrast
Setting up/connecting the virtual reality (VR) system, User interfaces, Moving around, Reading the content displayed on the screen, Identifying different objects, Seeing the color contrast, Contrast, Pointing to select, Sense of orientation, Haptic feedback (vibration when touching something), Viewing things up close, Viewing things from a distance
User interfaces
User interfaces, Moving around, Reading the content displayed on the screen, Identifying different objects, Seeing the color contrast, Contrast, Pointing to select, Viewing things up close, Viewing things from a distance
User interfaces, Reading the content displayed on the screen, Identifying different objects, Contrast, Pointing to select, Sense of orientation, Viewing things from a distance
can not see anything with no user accessibility to help navigate like i can do on a pc
Reading the content displayed on the screen, Identifying different objects, Sense of orientation, Viewing things up close, Viewing things from a distance
Reading the content displayed on the screen, Sense of orientation, Viewing things from a distance
Setting up/connecting the virtual reality (VR) system, User interfaces, Reading the content displayed on the screen, Identifying different objects, Seeing the color contrast, Pointing to select, Sense of orientation, Viewing things up close, Viewing things from a distance
Setting up/connecting the virtual reality (VR) system, User interfaces, Moving around, Reading the content displayed on the screen, Identifying different objects, Seeing the color contrast, Contrast, Pointing to select, Viewing things up close
User interfaces, Identifying different objects, Pointing to select, Viewing things up close, Viewing things from a distance
Setting up/connecting the virtual reality (VR) system, User interfaces, Moving around, Reading the content displayed on the screen, Identifying different objects, Seeing the color contrast, Contrast, Pointing to select, Sense of orientation, Haptic feedback (vibration when touching something), Viewing things up close, Viewing things from a distance
User interfaces, Reading the content displayed on the screen, Identifying different objects, Contrast, Viewing things up close, Viewing things from a distance
User interfaces, Reading the content displayed on the screen, Identifying different objects, Seeing the color contrast, Contrast, Viewing things up close
User interfaces, Reading the content displayed on the screen, Identifying different objects, Seeing the color contrast, Pointing to select, Sense of orientation, Haptic feedback (vibration when touching something), Viewing things up close, Viewing things from a distance
User interfaces, Moving around, Reading the content displayed on the screen, Identifying different objects, Seeing the color contrast, Contrast, Pointing to select, Sense of orientation, Viewing things up close, Viewing things from a distance
User interfaces, Reading the content displayed on the screen, Pointing to select, Sense of orientation, Viewing things from a distance
All
Everything
Reading the content displayed on the screen, Seeing the color contrast, Contrast
User interfaces, Reading the content displayed on the screen, Identifying different objects, Seeing the color contrast, Contrast, Viewing things up close, Viewing things from a distance
Everything
Setting up/connecting the virtual reality (VR) system, User interfaces, Moving around, Reading the content displayed on the screen, Identifying different objects, Seeing the color contrast, Pointing to select, Sense of orientation, Haptic feedback (vibration when touching something), Viewing things up close, Viewing things from a distance, Contrast
User interfaces, Sense of orientation, Viewing things up close, Viewing things from a distance
Setting up/connecting the virtual reality (VR) system, User interfaces, Moving around, Reading the content displayed on the screen, Identifying different objects, Seeing the color contrast, Pointing to select, Sense of orientation, Viewing things up close, Viewing things from a distance
User interfaces, Reading the content displayed on the screen, Identifying different objects, Seeing the color contrast, Contrast, Pointing to select, Haptic feedback (vibration when touching something), Viewing things up close, Viewing things from a distance
User interfaces, Reading the content displayed on the screen, Identifying different objects, Pointing to select, Sense of orientation, Haptic feedback (vibration when touching something), Viewing things up close, Viewing things from a distance
Setting up/connecting the virtual reality (VR) system, User interfaces, Reading the content displayed on the screen, Identifying different objects, Seeing the color contrast, Pointing to select, Sense of orientation, Viewing things up close, Viewing things from a distance, Im almost fully blind, so majority of these are hard for me to do without a screenreader
Pointing to select, Sense of orientation
User interfaces, Identifying different objects, Contrast
User interfaces, Reading the content displayed on the screen, Identifying different objects, Seeing the color contrast, Contrast, Pointing to select, Viewing things up close
Setting up/connecting the virtual reality (VR) system, User interfaces, Reading the content displayed on the screen, Identifying different objects, Pointing to select, Viewing things up close
User interfaces, Identifying different objects, Viewing things from a distance
User interfaces, Reading the content displayed on the screen, Identifying different objects, Seeing the color contrast, Contrast, Pointing to select, Viewing things up close, Viewing things from a distance
Setting up/connecting the virtual reality (VR) system, User interfaces, Moving around, Reading the content displayed on the screen, Identifying different objects, Seeing the color contrast, Pointing to select, Sense of orientation, Viewing things up close, Viewing things from a distance
User interfaces, Identifying different objects, Seeing the color contrast, Viewing things up close, Viewing things from a distance, Contrast
Identifying different objects, Seeing the color contrast, Contrast
User interfaces, Reading the content displayed on the screen, Identifying different objects, Seeing the color contrast, Contrast
User interfaces, Pointing to select
User interfaces, Reading the content displayed on the screen, Identifying different objects, Seeing the color contrast, Contrast, Pointing to select, Viewing things from a distance
User interfaces, Reading the content displayed on the screen, Identifying different objects, Pointing to select, Viewing things from a distance
Setting up/connecting the virtual reality (VR) system, User interfaces, Moving around, Reading the content displayed on the screen, Identifying different objects, Seeing the color contrast, Contrast, Pointing to select, Sense of orientation, Haptic feedback (vibration when touching something), Viewing things up close, Viewing things from a distance
User interfaces, Reading the content displayed on the screen, Identifying different objects, Seeing the color contrast, Contrast, Haptic feedback (vibration when touching something), Viewing things up close, Viewing things from a distance
User interfaces, Identifying different objects, Viewing things from a distance
Setting up/connecting the virtual reality (VR) system, User interfaces, Moving around, Reading the content displayed on the screen, Identifying different objects, Seeing the color contrast, Contrast, Pointing to select, Sense of orientation, Haptic feedback (vibration when touching something), Viewing things up close, Viewing things from a distance
User interfaces, Identifying different objects, Pointing to select, Viewing things from a distance
User interfaces, Reading the content displayed on the screen, Identifying different objects, Seeing the color contrast, Contrast
Reading the content displayed on the screen, Identifying different objects, Seeing the color contrast, Contrast
User interfaces, Identifying different objects, Seeing the color contrast, Contrast, Pointing to select, Viewing things up close, Viewing things from a distance
Reading the content displayed on the screen
Setting up/connecting the virtual reality (VR) system, User interfaces, Moving around, Reading the content displayed on the screen, Identifying different objects, Seeing the color contrast, Pointing to select, Sense of orientation, Haptic feedback (vibration when touching something), Viewing things up close, Viewing things from a distance
Moving around, Reading the content displayed on the screen, Pointing to select, Sense of orientation, Viewing things from a distance
User interfaces, Reading the content displayed on the screen, Identifying different objects, Seeing the color contrast, Contrast
User interfaces, Identifying different objects, Seeing the color contrast, Pointing to select
Reading the content displayed on the screen, Identifying different objects, Seeing the color contrast, Contrast
User interfaces, Reading the content displayed on the screen, Identifying different objects, Seeing the color contrast, Contrast
Sense of orientation
User interfaces, Reading the content displayed on the screen, Identifying different objects, Pointing to select, Viewing things from a distance
Reading the content displayed on the screen, Identifying different objects, Seeing the color contrast, Contrast
Setting up/connecting the virtual reality (VR) system, User interfaces, Identifying different objects, Pointing to select, Viewing things from a distance
Pointing to select, Viewing things from a distance
User interfaces, Reading the content displayed on the screen, Identifying different objects, Contrast, Viewing things from a distance
Identifying different objects, Seeing the color contrast, Contrast
User interfaces, Reading the content displayed on the screen, Identifying different objects, Seeing the color contrast, Contrast
Viewing things from a distance
Reading the content displayed on the screen, Pointing to select, Viewing things from a distance
User interfaces, Seeing the color contrast, Pointing to select, Contrast, Blurred vision and color blindness makes navigating the small interface hard for me
User interfaces, Identifying different objects, Seeing the color contrast, Contrast
User interfaces, Seeing the color contrast, Contrast
Moving around, Seeing the color contrast, Sense of orientation
Seeing the color contrast, Contrast
User interfaces, Pointing to select
Identifying different objects, Seeing the color contrast, Contrast
Reading the content displayed on the screen, Viewing things up close, Viewing things from a distance
none actually, my ophtamologist said that it might be precisely because of my vision defects that I feel more optically comfortable in VR than in the real world, I do use prescription lenses attached to my Valve Index eyecups
Seeing the color contrast, Contrast
Seeing the color contrast, Contrast
User interfaces, Seeing the color contrast, Contrast
Sense of orientation
Seeing the color contrast, Contrast

7. On a scale from 0 to 10: How essential is a screen reader for your ability to read the displayed text? 0 being not essential, 10 being significantly essential.	8. On a scale from 0 to 10: How essential are sound-location cues for you? 0 being not essential, 10 being significantly essential.
0	0
8	10
0	10
10	10
0	10
0	0
0	7
10	10
2	2
0	10
9	10
10	10
10	10
7	10
10	10
8	10
10	10
10	10
9	10
10	10
10	10
0	0
0	0
10	10
10	10
2	10
10	10
10	10
10	10
10	10
0	10
8	3
0	10
5	9
0	9
0	10
6	9
9	10
0	10
0	5
0	7
0	10
2	8
10	10
8	10
0	9
10	10
0	10
0	0
0	0
0	8
0	6
10	10
3	8
10	10
5	10
0	7
0	0
0	3
2	9
0	7
8	10
0	7
6	8
0	9
0	10
2	3
0	7
0	10
0	10
0	0
0	5
0	10
0	9
0	0
10	6
0	0
0	0
0	0
1	10
0	6
0	9

9. On a scale from 0 to 10: How essential is haptic feedback for you? 0 being not essential, 10 being significantly essential.	10. If you had to choose the MOST practical virtual reality (VR) feature for you, which one would it be?	11. If you had to choose the LEAST practical virtual reality (VR) feature for you, which one would it be?
0	Color and contrast enhancement	The immersion into the virtual world
0	Vision aid programs (Text to speech, zoom in)	Movement and motion tracking
0	Color and contrast enhancement	Movement and motion tracking
10	Color and contrast enhancement	Movement and motion tracking
0	Color and contrast enhancement	Movement and motion tracking
0	Color and contrast enhancement	The immersion into the virtual world
0	Vision aid programs (Text to speech, zoom in)	Movement and motion tracking
10	Spatial audio	The immersion into the virtual world
2	The immersion into the virtual world	Description of objects and surroundings
4	Description of objects and surroundings	The ability to communicate with others
4	Spatial audio	The ability to communicate with others
5	Spatial audio	The immersion into the virtual world
5	Spatial audio	Movement and motion tracking
7	Color and contrast enhancement	Movement and motion tracking
8	Spatial audio	The immersion into the virtual world
8	Vision aid programs (Text to speech, zoom in)	The ability to communicate with others
8	Spatial audio	The immersion into the virtual world
8	Vision aid programs (Text to speech, zoom in)	The ability to communicate with others
9	Spatial audio	The ability to communicate with others
10	Spatial audio	Vibration on the controller is useless
10	Spatial audio	Haptic feedback
0	Color and contrast enhancement	Movement and motion tracking
0	Color and contrast enhancement	Movement and motion tracking
10	Audio and Haptic in real life, vr lacks that	Movement and motion tracking
10	Spatial audio	Haptic feedback
7	Vision aid programs (Text to speech, zoom in)	The ability to communicate with others
10	Spatial audio	Movement and motion tracking
10	Spatial audio	The immersion into the virtual world
10	Spatial audio	The immersion into the virtual world
10	Spatial audio	The immersion into the virtual world
10	Spatial audio	The immersion into the virtual world
0	Spatial audio	Color and contrast enhancement
0	Color and contrast enhancement	The ability to communicate with others
2	Vision aid programs (Text to speech, zoom in)	Movement and motion tracking
3	Spatial audio	The immersion into the virtual world
6	Vision aid programs (Text to speech, zoom in)	Movement and motion tracking
7	Spatial audio	The immersion into the virtual world
9	Spatial audio	The immersion into the virtual world
0	Color and contrast enhancement	Movement and motion tracking
0	Color and contrast enhancement	Movement and motion tracking
0	Description of objects and surroundings	The ability to communicate with others
3	Color and contrast enhancement	The immersion into the virtual world
5	Description of objects and surroundings	Movement and motion tracking
10	Spatial audio	Movement and motion tracking
5	Vision aid programs (Text to speech, zoom in)	The ability to communicate with others
6	Description of objects and surroundings	The ability to communicate with others
10	Spatial audio	The immersion into the virtual world
10	Spatial audio	Movement and motion tracking
0	Vision aid programs (Text to speech, zoom in)	The immersion into the virtual world
0	Color and contrast enhancement	Movement and motion tracking
0	Color and contrast enhancement	The immersion into the virtual world
3	Vision aid programs (Text to speech, zoom in)	The immersion into the virtual world
10	Spatial audio	The immersion into the virtual world
3	Vision aid programs (Text to speech, zoom in)	Haptic feedback
10	Description of objects and surroundings	The ability to communicate with others
0	Vision aid programs (Text to speech, zoom in)	The ability to communicate with others
0	Color and contrast enhancement	The immersion into the virtual world
0	Color and contrast enhancement	Movement and motion tracking
3	Spatial audio	Color and contrast enhancement
6	Description of objects and surroundings	Haptic feedback
7	Color and contrast enhancement	The immersion into the virtual world
8	Vision aid programs (Text to speech, zoom in)	Movement and motion tracking
7	Color and contrast enhancement	The immersion into the virtual world
0	Vision aid programs (Text to speech, zoom in)	Movement and motion tracking
0	Color and contrast enhancement	The ability to communicate with others
0	Color and contrast enhancement	Haptic feedback
0	Movement and motion tracking	Haptic feedback
7	Vision aid programs (Text to speech, zoom in)	The immersion into the virtual world
10	Color and contrast enhancement	The ability to communicate with others
0	Color and contrast enhancement	The ability to communicate with others
0	Color and contrast enhancement	Movement and motion tracking
5	Color and contrast enhancement	Haptic feedback
7	Color and contrast enhancement	Description of objects and surroundings
9	Description of objects and surroundings	Movement and motion tracking
0	Color and contrast enhancement	Movement and motion tracking
5	The immersion into the virtual world	Color and contrast enhancement
0	none, in fact I don't even use the option for color blind people when available in games	.
0	Color and contrast enhancement	The ability to communicate with others
0	Color and contrast enhancement	Movement and motion tracking
0	Color and contrast enhancement	Movement and motion tracking
7	Movement and motion tracking	Vision aid programs (Text to speech, zoom in)
9	Color and contrast enhancement	The ability to communicate with others

12. On a scale from 0 to 10: Based on VRs current state of development, how willing would you be to use virtual reality (VR) for work or school-related meetings? 0 being very unwilling, 10 being highly willing.	13. Overall, would you say that virtual reality has an accessibility problem limiting its potential for visually impaired users?
0	Yes
0	Yes
0	Yes
0	Yes
0	Yes
0	Yes
0	Yes
0	Yes
0	Yes
0	Yes
0	Yes
0	Yes
0	Yes
0	Yes
0	Yes
0	Yes
0	Yes
0	Yes
0	Yes
0	Yes
0	Yes
7	Maybe
3	Yes
0	Yes
0	Yes
7	Yes
0	Yes
0	Yes
0	Yes
0	Yes
0	Yes
1	Yes
2	Yes
2	Yes
2	Yes
2	Yes
2	Yes
2	Yes
3	Yes
3	Yes
3	Yes
3	Yes
3	Yes
0	Yes
3	Yes
3	Maybe
3	Yes
3	Yes
4	Yes
4	Yes
4	Yes
4	Yes
0	Yes
4	Yes
4	Yes
5	Yes
5	Yes
5	Yes
5	Yes
5	Yes
5	Maybe
5	Yes
6	Yes
7	Yes
7	Maybe
7	Yes
7	Maybe
7	Yes
7	Yes
8	Yes
8	Yes
8	Maybe
8	Maybe
8	Yes
9	Yes
9	Maybe
10	No
10	Maybe
10	Maybe
10	Maybe
10	Maybe
10	Yes