Bearbeitungsbeginn: 01.09.2022

Vorgelegt am: 28.02.2023

Thesis

zur Erlangung des Grades

Bachelor of Science (B.Sc.)

im Studiengang Medieninformatik

an der Fakultät Digitale Medien

Umberto Falkenhagen

Matrikelnummer: 260601

Pilotstudie zur Untersuchung des Einflusses von Interaktionen im Nahbereich des Menschen in Virtual Reality auf die Entstehung visuellen Unbehagens

Erstbetreuer: *Prof. Nikolaus Hottong*

Zweitbetreuer: *Prof. Thomas Krach*

Abstract

Lately, virtual reality has become more and more popular. Large companies like Meta and HP Inc. have invested huge amounts of resources into developing new virtual reality headsets and content, while ideas like the Metaverse have caught the public eye. But despite its rising popularity, virtual reality remains a field with many open questions. The immersive and three-dimensional nature of VR forces us to design applications in different ways, shifting the focus from creating applications to creating virtual environments. In this work, interactions within the personal space in virtual reality and how they affect visual discomfort were investigated. Technical limitations, mainly those of so-called head-mounted displays, as well as perceptual problems as discussed in current research are displayed. Following that, a user test will be created to test the influence of such interactions in practice. From this information, I created guidelines for implementing these kinds of interactions in virtual reality.

Table of Contents

List of Figures

List of Abbreviations

3D .... *three-dimensional*

CAVE .... *CAVE Automatic Virtual Environment*

CIM .... *Computer Input Modalities*

COM .... *Computer Output Media*

HCI .... *Human-Computer Interaction*

HIC .... *Human Input Channels*

HMD .... *Head-Mounted Display*

HOC .... *Human Output Channels*

IQR .... *Interquartile Range*

PC .... *Personal Computer*

SSQ .... *Simulator-Sickness Questionnaire*

UX .... *User Experience*

VAC/VA conflict .... *Vergence-Accommodation conflict*

VE .... *Virtual Environment*

VR .... *Virtual Reality*

1 Introduction

In recent years, virtual reality (VR) has turned from a small alternative gaming option into an industry-changing factor. Unfolding its huge potential in many industries and "weaving itself into the fabric of our modern lives" (HP 2020). As part of this change, many industries such as the medical, engineering, and educational sectors have implemented virtual reality in their work routines. Today more than ever, we are using VR to work together remotely, to create safe training environments for high-risk jobs, and to help us do many of our jobs more efficiently. These opportunities led to a huge growth in the market which is "projected to increase from less than five billion U.S. dollars in 2021 to more than 12 billion U.S. dollars by 2024" (Alsop 3/22/2021).

Furthermore, the use of VR has a lot of advantages for users. Studies in the training sector have shown multiple improvements when using VR training compared to other methods like classroom learning or e-learning (PwC 2022). They have shown that using virtual reality can save significant amounts of time for the learners as seen in Figure 1 and reported other positive side effects. The subjects of the survey showed an increased focus while also forming stronger emotional connections to the learning content. This allowed them to remember the

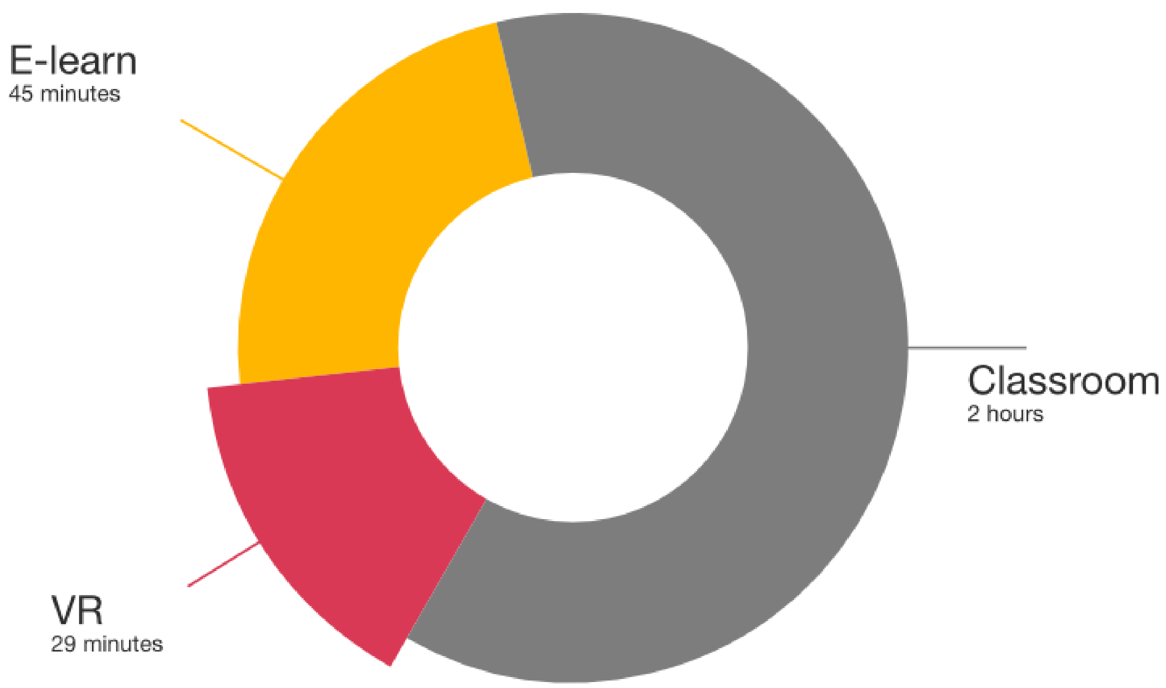

Figure 1: Time to complete training (PwC 2022)

contents more easily in the long-term, while also making them feel more confident when applying it to their work.

But despite these developments, VR is still considered to be a relatively new kind of media which comes with strings attached. As we are moving towards a more digitalized world and trying to transport real-world interactions into a virtual environment, issues of designing such interactions clash with the current limitations of the used devices and our perception.

In this work, I investigate one of the core problems when it comes to our perception of VR, namely the vergence-accommodation conflict. I will explain its roots and consequences for the design of interactions within the human personal space.

I will focus on visual perception in VR. Specifically on the use of so-called Head-mounted-displays (HMDs) which use stereo imagery to create virtual environments. It will start by giving insights on what VR means, how HMDs work, how we can define interactions as well as the personal space, and finally how all of this results in the priorly named vergence-accommodation conflict and other issues. Using this knowledge, the author will create and execute a pilot version of a user test to answer the questions if interactions in the personal space within VR are influencing visual discomfort of users and whether it is possible to identify interactions that are more influential than others. Ultimately, the goal of this work is to provide advice for implementing such interactions and give indications of where they might add to the overall user experience and where they might cause issues.

2 Theoretic Background

This chapter aims to establish a common ground of knowledge. To achieve that, the topic of this work was split up, providing essential information on the different subtopics. Firstly, I took a look at virtual reality, how this term can be defined, and how it has evolved over the course of its history. Following that, I focused more on head-mounted displays and how they work. After that, I dived deeper into the topic of interactions as well as the human personal space. Finally, this chapter concludes by giving insights into the issues of visual discomfort in VR, and more specifically the vergence-accommodation conflict.

2.1 Virtual Reality

In this chapter, I aimed to give a better understanding of modern VR technology. I use existing literature to provide a definition as well as an overview on the history and development of VR technologies throughout the past decades. Following that, I compared different modern-day VR technologies.

2.1.1 What is virtual reality?

When defining what virtual reality is or might be, it only comes naturally to define both parts of this term individually. In his book *"The VR Book: Human-Centered Design for Virtual Reality"* Jason Jerald discusses these meanings, citing from a dictionary that *virtual* could be defined as "being in essence or effect, but not in fact" (Webster 1989). He also cites the definition of *reality* as "the state or quality of being real. Something that exists independently of ideas concerning it. Something that constitutes a real or actual thing, as distinguished from something that is merely apparent" (Webster's New Universal Unabridged Dictionary, 1989). While he points out that these two words contradict one another, he ultimately comes to combine them and define virtual reality as "a computer-generated digital environment that can be experienced and interacted with as if that environment were real" (Jerald 2015, S. 9).

Another description of virtual reality and its properties can be found in the Multimodal Technologies and Interaction journal. In this article, Cruz-Neira states that "overall, VR can be referred to as a technology that allows for replacing the real world by a synthetic one, making the user believe that she/he is in another realm. It involves a set of technologies that are used to create computer-generated virtual environments where users can experience and interact just as if they would do in real life. To that end, it integrates stereoscopic displays, motion tracking hardware, input devices, and software platforms" (Cruz-Neira et al. 2018).

The definitions provided by Jerald and Cruz-Neira already indicate prominent features when thinking of virtual reality:

- **3D-simulated environment:** An artificial environment is rendered through a medium such as a VR display or a headset. The user's visual perspective changes based on movements occurring in the real world.
- **Immersion:** The environment is realistic enough where you can effectively recreate a realistic, non-physical universe so that a strong suspension-of-disbelief is created.
- **Sensory engagement:** VR can include visual, audio, and haptic cues that help make the immersion more complete and realistic. This is where accessories or input devices such as special gloves, headsets, or hand controls provide the VR system with additional input of movement and sensory data.
- **Realistic interactivity:** The virtual simulation responds to the user's actions and these responses occur in a logical, realistic manner (HP 2020).

By looking at these aspects of VR, it becomes clear that VR describes more than just a single technology. It is an approach to creating things that look, behave, or feel real although they are not. To achieve that we have invented different technologies, gathered knowledge about our perception of reality, and combined them to create things that would make us think that they are real. However, we are still far away from perfecting this "art of faking reality". The following chapter about the history of VR shows that we have come a long way. Still, our current technologies have a wide range of limitations, and we lack an understanding of how humans perceive reality, resulting in many issues when creating the ultimate virtual reality, if there is one.

Concluding this chapter, this work uses a shortened version of Cruz-Neira's definition, thus defining VR as "a set of technologies that are used to create computer-generated virtual environments where users can experience and interact just as they would in real life. It aims to replace the real world with a synthetic one.” Based on this definition, it becomes clear, that it is important to choose which set of technologies should be investigated. Not just because the sheer number of options is way beyond the limits of this work, but also because the problems of each set may vary greatly depending on the underlying mix of technologies. Thus, as mentioned before, this work investigates the technologies used in head-mounted display headsets. Furthermore, it reveals the cause of this work. In alignment with the goal of VR to replace the real world with a synthetic one, this work aims to minimize issues caused while using such headsets in order to increase the immersion of VR applications.

Ultimately, we can only speculate where new technologies and other advances in science will lead us. For example, Ivan Sutherland, the creator of one of the world’s first VR systems, stated that “the ultimate display would, of course, be a room within which the computer can control the existence of matter. A chair displayed in such a room would be good enough to sit in. Handcuffs displayed in such a room would be confining, and a bullet displayed in such a room would be fatal” (I. Sutherland 1965).

2.1.2 The history of (head-mounted) virtual reality

The prior chapter already revealed that virtual reality is not a single technology but an idea driven by the purpose of “creating the illusion of conveying that which is not actually present” (Jerald 2015, S. 15). While this goal has remained the same throughout time, our ways of achieving it have evolved quite a lot. This chapter aims to dive deeper into the history of virtual reality. Since the research presented in this work focuses on head-mounted displays, this chapter focus on that specific kind of technology.

When we think of modern VR technologies, the head-mounted display is arguably the most prominent technique for virtual reality. However, the underlying technology for these modern headsets was already invented by Charles Wheatstone in 1832. As shown in Figure 2, he used mirrors placed at a 45° angle to project an image into the eyes from both sides. Not even 20 years later in 1851, David Brewster “had developed his lenticular stereoscope, a box-like instrument with two decentered lenses and a hinged shutter on top to admit light” which can be seen in Figure 3 (Zone 2007, S. 10–11). The device was a huge success and was sold over half a million times by 1856. Naturally, these stereoscopes were very far from what we are

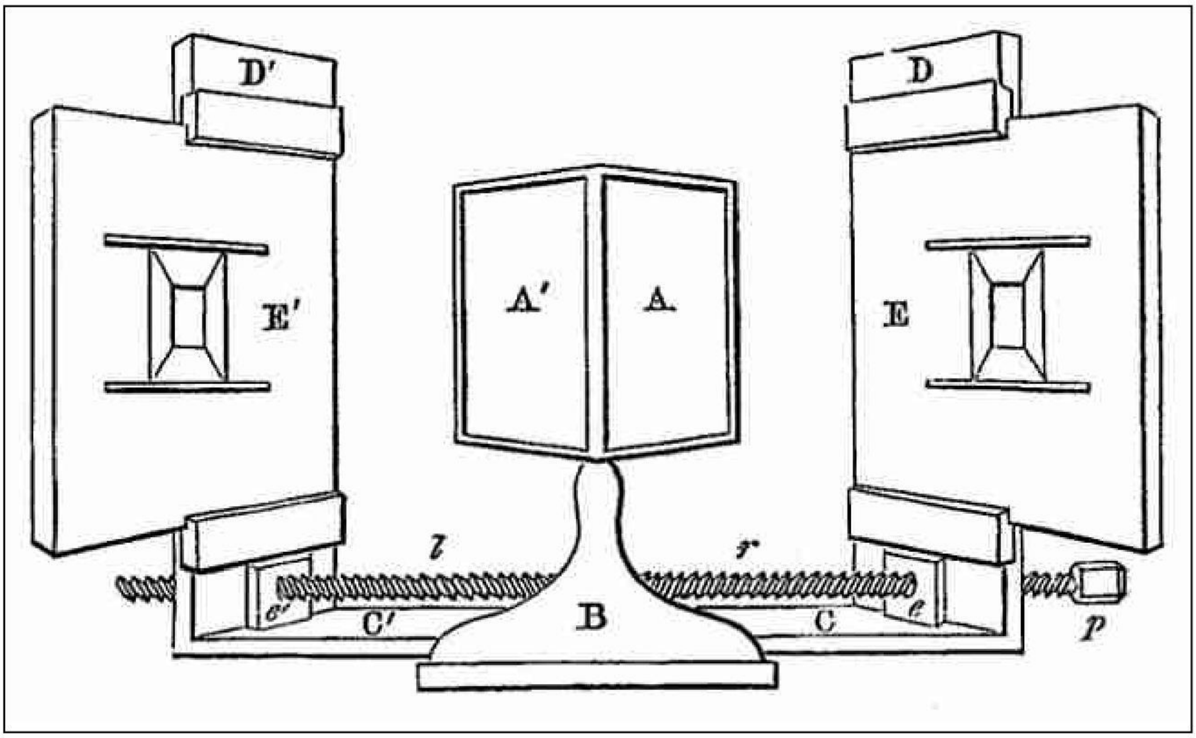

Figure 2: The earliest form of Charles Wheatstone's stereoscope (1833). (Zone 2007, S. 6)

using today but as the name suggests they already used the same technique which we still use to display 3D imagery in VR headsets today. In the following years, these stereoscopes became one of the first mass media devices. With cheap devices and abundant imagery, stereoscopic viewing came within reach of a broad middle-class audience. Historian William Culp Darrah estimated that between 1860 and 1890 as many as 12,000 stereo-photographers took between 3.5 and 4.5 million individual images, which were printed on upwards of 400 million stereographs (Stereoscopes | Encyclopedia.com 2022). However, some experimental developments within the stereoscopes industry already showed a trend towards a newly emerging type of media. Instead of just looking at a three-dimensional picture, people longed for more and thus tried to build machines that could display several different pictures which oftentimes implied a narrative. With the first of such devices already being patented in 1857 by Alexander Becker, this idea would lay the foundation for motion picture technologies that would take over the stereoscope's popularity at the beginning of the 20th century. Thus it can be said that the stereoscopes were not just a predecessor but instead one of the driving engines behind the development of modern motion picture systems. (Zone 2007, S. 15) The popularity of stereoscopes lasted for almost 70 years. Only "with the emergence of cinema, and especially after the 1920s, the stereoscope became largely an educational tool and later a children's toy" (Stereoscopes | Encyclopedia.com 2022).

With the end of stereoscopes as mass media devices towards the middle of the 19th century, head-mounted displays moved out of the public focus. However, the emergence of other technologies would become crucial to achieving the kind of headsets that we use for VR today. As previously mentioned, the first half of the 20th century saw the rise of motion picture technologies without which we could not display dynamic environments within VR. Furthermore, during that time, people also tried out new interaction methods such as the creation of the first simple mechanical flight simulator. Simultaneously, the short story “Pygmalions Spectacles” told readers of a type of headset that could replace real-world stimuli with artificial ones to a degree at which the main character becomes convinced that it is real (Jerald 2015, S. 18–20).

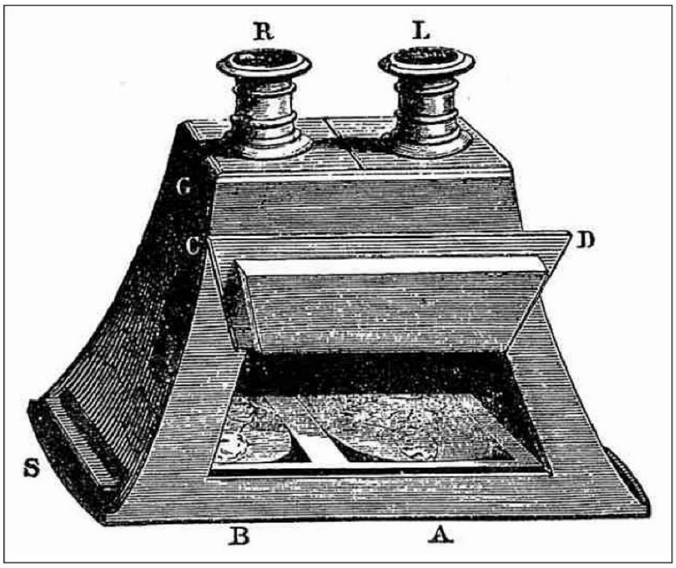

Figure 3: David Brewster’s lenticular stereoscope (1851). (Zone 2007, S. 11)

After 1950 the HMDs had a great comeback and research focused on their development once more. Based on the enormous advance in technology that had happened since, inventors created the first designs for head-mounted displays which included lenses that could display wider angles to include larger portions of the human field of view as well as stereo sound, head tracking, and other immersive components. “In 1961, Philco Corporation engineers built the first actual working tracked HMD that included head tracking. As the user moved his head, a camera in a different room moved so the user could see as if he were at the other location. This was the world’s first working telepresence system” (Jerald 2015, S. 21). And in 1968 Ivan E. Sutherland demonstrated the “Sword of Damocles” an HMD with which “he transformed this “remote reality” into “virtual reality” by replacing the cameras with computer-generated scenes with which the viewer could interact” (Oakes 2007, S. 702). During that time further work for the creation of the foundations of modern VR technologies began. Different research programs as well as some smaller companies were founded that explored smaller subareas of virtual reality. In 1962, for example, IBM patented the first glove input device in contrast to the commonly used keyboard.

Finally, in 1985 "NASA researchers developed the first commercially viable, stereoscopic head-tracked HMD with a wide field of view, called the Virtual Visual Environment Display (VIVED). […] The VR system was unprecedented as the HMD could be produced at a relatively affordable price, and as a result, the VR industry was born (Jerald 2015, S. 26). Following that, the popularity of VR increased drastically at the beginning of the 90s. This led to the founding of many companies focused on the development of VR and wild speculations on VR becoming the next mass media phenomenon, used by people during bus or train rides, in the near future (Negroponte 1993). However, as the end of the century drew closer it became clear that technology could not support what was promised and most of the companies went out of business as fast as they appeared.

This initiated the so-called "VR winter" which lasted for the first decade of the 21st century. While VR moved out of public focus once again, the research on its technologies continued. However, the focus of projects slowly shifted to a human-centered design aimed to increase the immersion provided by such headsets (Jerald 2015, S. 27). This research revealed many basics of today's headsets, for example, the importance of a wider field of view angles to allow for the better judgement of distances (Jones et al. 2012, S. 119).

After being off the radar for some time and shortly after the end of that first decade, new prototypes were created and demonstrated to the public. This led to the creation of a Kickstarter campaign for the "Oculus Rift" headset. Not even two years later Facebook, now Meta, purchased the company for $2 billion (Kumparak 3/26/2014). At the same time, many other companies began to see the potential of VR and started investing. Thus, the winter was finally overcome, and the current period of VR began. Within the past years, the market has widened significantly with more headsets being released constantly by companies such as Meta, Vive, Valve, HP, and many more.

To widen the view a little bit more the next chapter will focus on the different methods of VR that are used nowadays.

2.1.3 Types of VR systems

As discussed before, this work views VR not as a specific technology but as a combination of such. Furthermore, the previous chapter has shown that the idea of virtual reality has been around for quite some time. Its history led to a wide range of alternative technologies which are used to create VR systems. In this chapter, the author will give an overview of current VR systems and highlight their features, as well as their advantages and disadvantages when compared to one another. Thus, the goal of this chapter is to provide an understanding of how the author came to choose HMDs for this study.

However, before diving deeper into such methods, we must first discuss the term (virtual) reality systems. A reality system is a hardware and operating system upon which full sensory experiences are built. The reality system’s job is to effectively communicate the application content to and from the user in an intuitive way as if the user is interacting with the real world.[...] Ideally, the technology will not be perceived so that users forget about the interface and experience the artificial reality as if it is real (Jerald 2015, S. 30). It seems natural that with different applications the underlying systems would have to adjust as well. With that in mind, it is also important to differentiate such systems in regard to how they virtualize reality. Figure 4 shows the virtuality continuum as described by Milgram and Kishino. It ranges from a completely real environment (One could also say “reality”) to a completely virtual environment (one, that is entirely computer-generated). In between, it shows transitioning forms between both kinds of environments with AR meaning augmented reality which describes real environments to which virtual cues are added. As an example, imagine an application that lets you equip your (real) room with not yet ordered (virtual) furniture. In contrast, AV means augmented virtuality which describes the capturing of real-world content and bringing it into virtual environments. This could for example include immersive films.

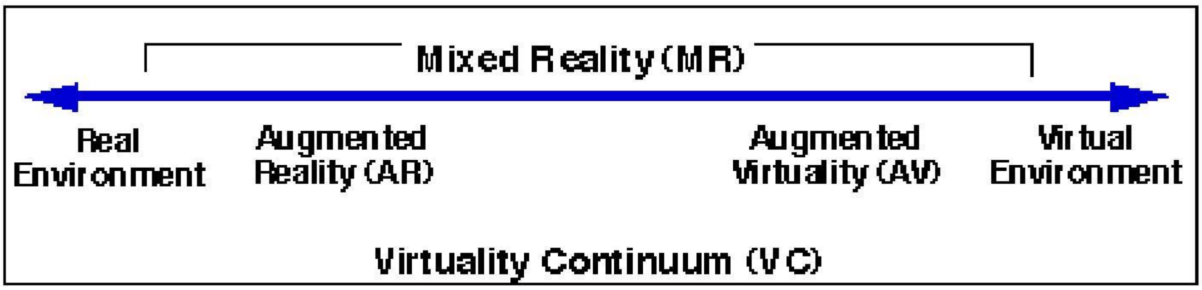

Figure 4: Simplified representation of a "virtuality continuum" (Milgram und Kishino, S. 3)

In this work, the author will focus on reality systems that display entirely virtual environments. This narrows the number of comparable systems down to three different core techniques. In modern reality systems, these are namely head-mounted displays, world-fixed displays, and hand-held displays, which will be discussed shortly. It should be noted that while it seems like this continuum only focuses on visual components of reality systems, it can also be applied to audio or other sensory components.

2.1.3.1 Hand-held displays

Hand-held displays are arguably the simplest but also the most restricted form of displaying virtual environments. As the name states, they are being held with the users' hands. Due to many restrictions, especially when it comes to interacting with the virtual environment, they are often described as a form of indirect VR. Firstly, they seldom use head-tracking and due to being held by the user must rely on simple interactions like touching parts of the screen (Jerald 2015, S. 34).

While it is arguably the most versatile reality system of all three, due to its small systems requirements, it is also the one that is least associated with VR. An example of the use of this technology is playing a game on a tablet or smartphone. While the device would only display entirely virtual environments, it certainly falls short of interactions that feel real. It is almost impossible to reach the point of suspension of disbelief with such devices as they mostly fail to isolate the user from the things happening around them and seldom display the contents in 3D just to name a few factors.

As a result, this technology is not suited for this work as it does not align with the basic intent to work with virtual environments that feel real to the user.

2.1.3.2 World-fixed displays

In its simplest form, a world-fixed display just describes a single monitor that does not move, at least most of the time. In VR-related systems, this oftentimes means that the position of the display does not move according to the user's head movement. Due to this, VR systems that use this technique often include several such displays to cover a wide area of the user's Field of View or even surround them (Jerald 2015, S. 33–34). Systems of that kind are called CAVE's which stands for "CAVE Automatic Virtual Environment", thus being a recursive acronym. As described by Cruz-Neira a CAVE "is a virtual reality interface. [...] It consists of a room whose walls, ceiling and floor surround the viewer with projected images" (Cruz-Neira et al. 1992, S. 65).

Modern CAVE systems involve complex sets of technologies and can provide a highly immersive experience. Some go as far as moving the displays around the user to increase immersion, while other versions of these systems are used in modern movie productions to replace green screens and display 3D-generated backgrounds. Systems, that employ such technologies have some advantages as they surround the user, thus eliminating the problem other systems have with covering the human field of view. Furthermore, in contrast to HMDs, they are nonintrusive, meaning that they impair the user's senses less (Cruz-Neira et al. 1992, S. 71).

However, due to their complicated setup, they are the most expensive VR method not just in price but also in the use of space (Jerald 2015, S. 34). This limits their use to very few scenarios. In most cases they are employed in business environments, such as the mentioned production of movies. Other examples can be found in VR applications for engineering or pilot training. However, due to their costs, such systems are at least currently not accessible to most people. A simplified setup of a CAVE system is displayed in Figure 5. Yet, despite being a fully functional alternative to HMDs, there is one issue that rules such systems out for the investigation done

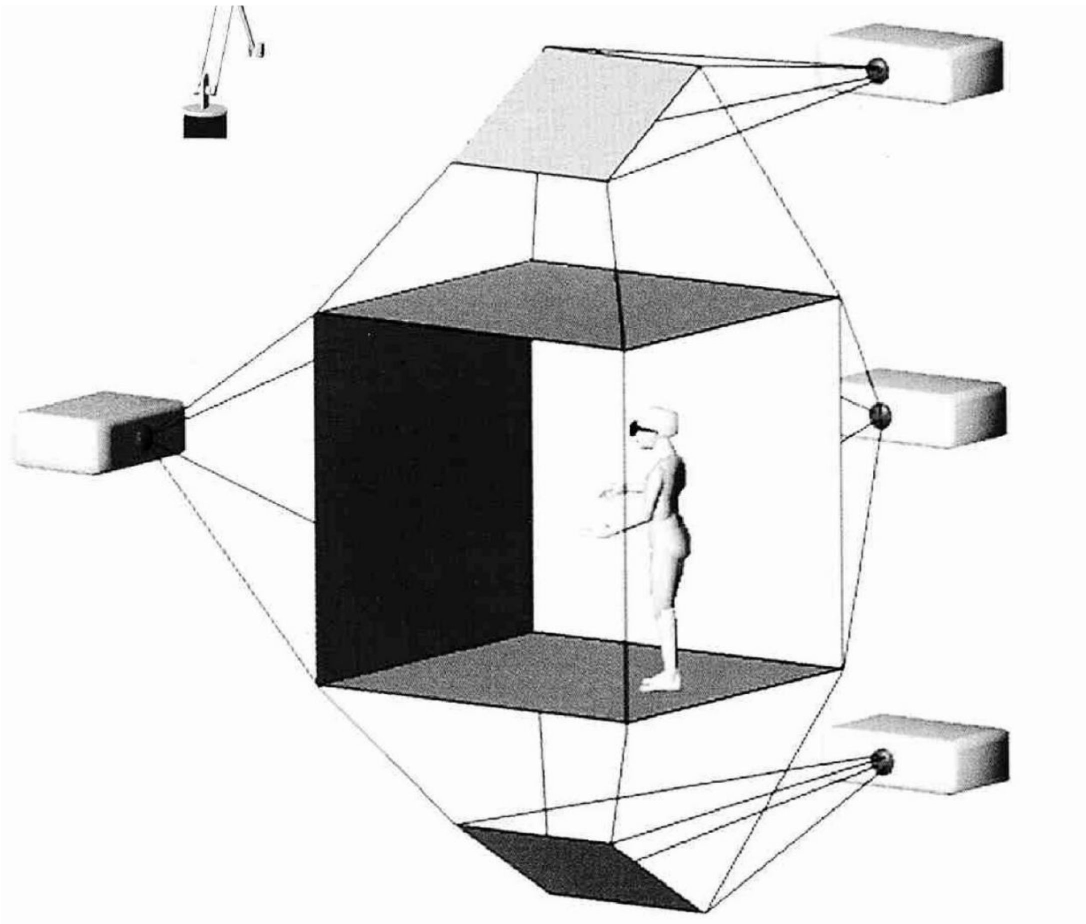

Figure 5: Simplified setup of a CAVE system (Cruz-Neira et al. 1992, S. 66)

in this work. They do not struggle with the vergence-accommodation conflict. However, this technique is also not a solution to that issue, as it aims to investigate interactions in the personal space. Simply due to the setup, the user can neither interact nor get close to the objects rendered on the displays.

2.1.3.3 Head-mounted displays

In contrast to the previously discussed world-fixed displays, HMDs place a screen in front of each of the user’s eyes. As the name suggests, they are mounted on the user’s head and thus attached to his movement. The view, representing the segment of the virtual environment generated and displayed, is controlled by orientation sensors mounted on the "helmet''. Using the information provided by those sensors, the head movement is recognized by the computer, and a new perspective of the scene is generated according to the head’s position. In most cases, a set of optical lenses and mirrors are used to enlarge the view to fill the field of view and to direct the scene to the eyes (Perry et al. 1997).

Head-mounted displays (HMDs) often cause discomfort and even nausea. Improving comfort is therefore one of the most significant challenges for the design of such systems (Koulieris et al. 2017, S. 1). Modern versions of such displays are the direct successors of the techniques that were already discussed in the previous chapter on the history of virtual reality. In this sense, they display stereoscopic images using screens to separate images one for each eye. Positioned between the screen and the eye are lenses to enlarge the image displayed on the screens to cover a wider area of the human field of view (Shibata 2002, S. 57).

This basic architecture, as illustrated in Figure 6, is the same for most HMDs today. The differences between modern headsets are largely found in other limitations like the resolution of the displays, the frame rate that they can support, or how much of the human field of view they cover. However, due to the shared architecture, they also share common problems, one of which is the vergence-accommodation conflict (or shortly the VAC). Details on this issue will be discussed in later chapters.

Yet even with this issue at hand, these headsets have become the most popular reality systems in the modern VR market and many different versions have been invented. One of the most common categorizations of HMDs is to differentiate between mobile and tethered

HMDs. While this differentiation is originally just based on the location where the data is processed, it also allows us to assume some limitations of a system.

Mobile HMDs became very popular around 2010 when different companies and manufacturers like Google and Samsung released VR devices that allowed customers to use their smartphones as displays and processing devices. To keep the setup simple and due to large differences between different smartphones, most of these headsets do not use controllers. However, this also severely limits their options for interacting with the virtual environment, while the relatively small processing power of most smartphones further limits the complexity of available applications. As a result, these headsets are preferred for small showcases and 360-degree videos (Cervantes 2/25/2022).

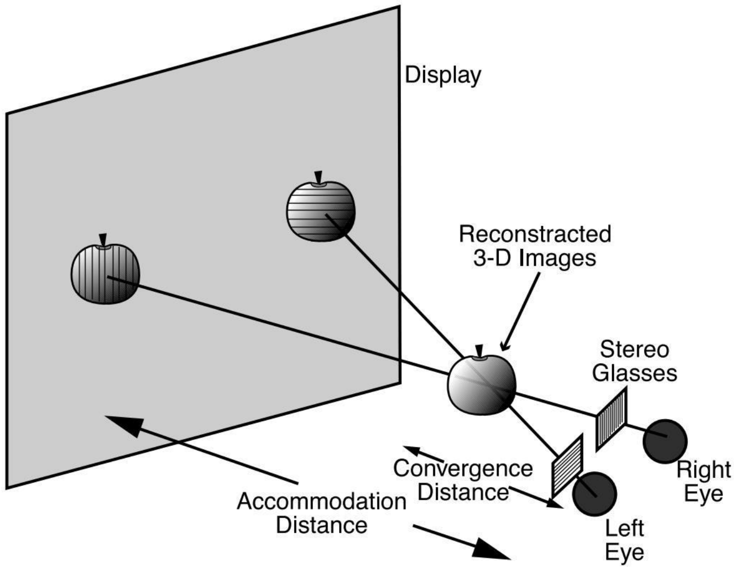

Figure 6: Stereoscopic 3D display and the mismatch of the distance between accommodation and convergence of the human eyes (Shibata 2002, S. 59).

However, in recent years, a new version of mobile headsets has conquered the market. So-called standalone HMDs are headsets that process all data within the device without the use of a smartphone as the screen. As the name suggests, they include all components necessary for VR and function as an independent device. The most famous examples are the Quest series developed by Oculus, which belongs to Meta. While they are still limited in their processing power compared to tethered devices, they offer complex applications as well as interactions and have undoubtedly led to huge growth in the market, as can be seen in Figure 7.

Alternatively, tethered VR headsets are devices that are connected to a PC via a cable. Such headsets typically require more computing power, but in exchange deliver superior VR experiences like higher-quality graphics or more diverse environments. The architecture of tethered HMDs remains pretty similar to the prototypes prior to the beginning of the 21st

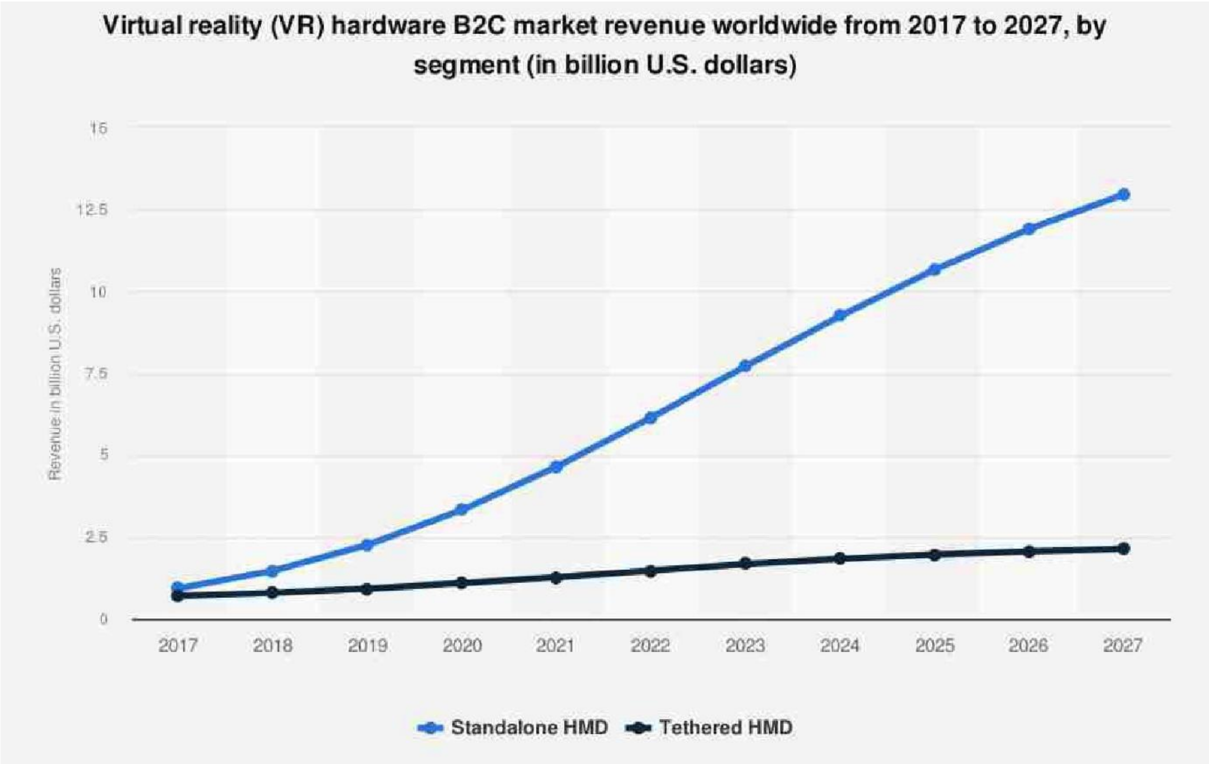

Figure 7: Standalone HMDs have become very popular and have overtaken tethered HMDs in sales (Statista 2022)

century and has been at the center of VR development ever since that time. While they are not as mobile as the previously mentioned mobile and standalone HMDs, they offer benefits based on the connected PC. In contrast to the standalone HMDs, which must include processors, sensors, batteries, storage memory, and displays, these headsets can also focus on sensory and display technologies. Thus, they oftentimes offer displays with higher resolutions, higher-quality graphics, higher frame rates, and more (Alsop 2022). Popular examples of this kind of HMD are Sony's PlayStation VR, the HTC Vive Series, and the HP Reverb G2 which will be used in this study.

The previous chapters on the topic of virtual reality explored the historic and modern-day technologies used to create VR experiences. Detailing the VR technology in usage (in this case head-mounted displays) and narrowing the possible options down to a specific headset (the HP Reverb G2) are critical steps in order to design the user test, which will be described later in this work. However, the following chapter will deal with interactions, more specifically those in VR, to identify important parameters for the application used in the test.

2.2 Interactions

The following chapters aim to provide insights into the topics surrounding interactions in virtual reality. With that in mind, the author will first define the term “interaction”. Following that, the author will specify the meaning of interactions within the context of virtual reality using a model that illustrates the interaction between humans and virtual environments. Based on these observations and concluding this chapter, the author will then provide an overview of the relevant interactions within the personal space in VR.

According to the Cambridge English Dictionary, the term interaction describes "an occasion when two or more people or things communicate with or react to each other." (Cambridge English Dictionary: Meanings & Definitions 2023). In other words, an interaction could be defined as the communications or influences between two things. This causes things to interact at all levels, from the smallest to the largest. Interactions might happen between two atoms that push each other away or pull them closer. Additionally, interactions also take place when we talk to another person, for example, and they might in turn react with certain actions. On larger scales, we can also describe interactions between the planets of our solar system or even between galaxies as they influence each other through gravity. Due to the sheer size of this topic, it is necessary to specify the field of research as well as the kinds of interactions that are being investigated. Thus, as mentioned previously, the author will focus on interactions within VR and more specifically such that happen within the human’s personal space.

2.2.1 The human-VE interaction model

After previously defining the term “interaction”, this chapter will discuss a model proposed by L. Schomaker which illustrates the way we as humans interact with virtual environments like in VR.

As stated in the handbook of virtual environments, such environments represent "advanced, immersive, human-computer interaction (HCI) systems" (Stanney 2015, S. 411). The interactions within such systems are multimodal, meaning that they use a group of different channels as communication pathways. Figure 8 shows the “human-VE interaction model” and was taken from L. Schomaker (1995). According to the definition of interactions in general, he also assumes that a minimum of two separate agents must be involved – a human and a machine. Since they are separated, they use several input and output channels or “modalities” to communicate and exchange information. Based on the view of a human in this scenario, he further points out that there are three processes involved in exchanging information: Perception, Control, and Cognition.

The process of perception covers the “Computer Output Media” (COM) and the “Human Input Channels” (HIC) and therefore describes "the process of transforming sensorial information to higher-level representations" (Stanney 2015, S. 412). Taking the use of a VR headset as an example, the HMD (the computer) communicates the generated virtual environment using different COMs, like the displays (visual channel), speakers (auditive channel), or the controllers (haptic channel). The human, however, perceives these cues with their different HICs, for example, their eyes (receiving visual information), ears (audio), and haptic sense.

The process of control, on the other hand, includes the “Human Output Channels” (HOC) and the “Computer Input Modalities” (CIM), and thus "represents the translation of human actions into task-related information for the computer" (Stanney 2015, S. 412) Sticking to the previous example, the human individual communicates their behavior within the virtual environment through different HOCs, for example, motion (including gestures), touch (like touching buttons on the controller), speech, or gaze. The information provided through the HOCs is then translated into relevant information for the computer using its CIMs. This could include various modalities like motion or gesture tracking tools, microphones (capturing speech commands), or tools that track touch input (like a controller).

The third process, namely cognition, takes place on both sides of the interaction. While we as humans process the information provided by our senses and react accordingly, so does the computer. However, two things about this interaction loop should be noted. Firstly, we know the design of the computer cognition process, but we can only assume the processes happening inside our human brains (L Schomaker 1995, S. 2). Secondly, it is known that "present limitations lay at the computers side of the interaction loop" (Stanney 2015, S. 412).

Another important detail considered about this model is the so-called “intrinsic perception/action loop”. This loop represents the way we ideally perceive the interaction with the virtual environment. It means that we as humans should not note the steps happening between our actions and the responding reaction of the environment. If such delays should happen within the communication, it would certainly disturb the immersion if not completely disable the interaction with the system in case of significant delays. This means that this delay between receiving human input information and reactive outputs from the computer must be kept as short as possible.

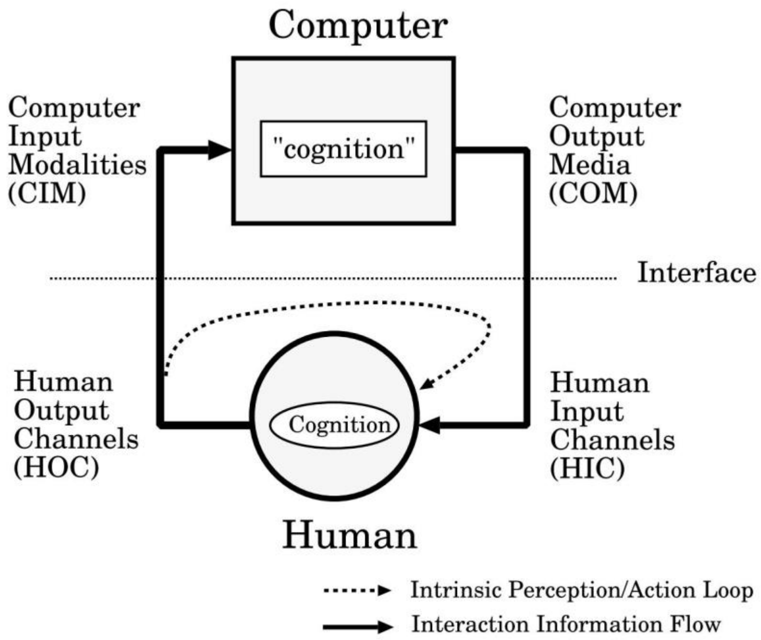

Figure 8: A model for the identification of basic processes in human-computer interaction. (L Schomaker 1995, S. 2).

As a result of this model, it is possible to conclude that interactions are a matter of scope. Thus, within this work, an interaction is seen as a loop of communication between at least two agents in which the input and output modalities (or channels of communication) of both agents can be identified. As such, this model can be used to describe the general use of an HMD as well as relevant factors influencing the user throughout the experience. However, applying it to certain instances of such an experience helps to identify interaction loops and to analyze the factors relevant to a specific interaction. This will be done in the next chapter to create an overview of possible interactions within the personal space in VR.

2.2.2 Interactions in the personal space

Schomaker (1995) developed a layered model for interactions in virtual environments based on the previously presented interaction model. This model can be seen in Figure 9 as it was adapted in the Handbook of Virtual Environments. It allows us to investigate applications and the interactions they contain more easily by creating a hierarchy in which the different layers help to categorize interactions based on certain attributes.

Layered Model for Interaction in VE

Application	**Virtual Reality, CAD, Visualization, Architectural Design**
Interaction tasks	Navigation, manipulation (move, rotate, scale), identification, selection, VE editing
Interaction techniques	Gesture language (grabbing, releasing, pointing), 3D menu, speech commands, gaze commands, multimodal commands
Events	Hand and body gestures, 3D motion, button click, force, 2D motion, torque, spoken units, eye motion, gaze direction
Input devices	Sensing gloves, trackballs, 3D mouse, 6D tracker, eye tracker, joystick, microphone, tactile gloves

Figure 9 Layered Model for Interaction in virtual environments as presented in Stanney (Hg.) 2015 adapted from Schomaker, L. et al. (1995) (Stanney 2015)

At the top of the hierarchy (ignoring the application layer) lies the task, that the interaction should resolve. As such, there are 5 different types of tasks, each of which can be resolved through different combinations of techniques, events, and input devices. Navigation, for example, describes all tasks that include moving the user's avatar through the virtual environment. Such a task could be implemented through different techniques, like the use of gesture language, which could then in turn be based on certain events, like specific button clicks or hand gestures. By using a joystick or even the whole controller as an input device, these events can be recorded, therefore offering modalities to allow communication between the user and the VR system. While the layers are independent of one another, it is important to note that some modalities are suited better for solving certain tasks (Stanney 2015, S. 415).

Applying this model, it is now possible to identify different interactions that are used within VR. To do so, the author investigated different VR applications and analyzed the interactions they contained. Since this investigation focuses on interactions in the personal space, a separate attribute was added, the distance between users and the interactive objects. This attribute determines directly whether an interaction happens within the personal space or not. As a result, it is important to specify the meaning of personal space. There are many instances of this term throughout literature. Often it is used in a sociological context, referring to it as "the distance from another person at which one feels comfortable when talking to or being next to that other person" (Merriam-Webster.com Dictionary 2023). In this work, however, the term will be simplified and thus only used to describe the average distance between the eyes of the user and an interactive object. Since exact distances in virtual environments are hard to measure, the author decided to use the length of the user's arms to assume the distance. Therefore, every object that can be reached by the user's hands is within the personal space. While the individual arm length may vary, this approach still allows for a rapid assumption of the distance.

As mentioned previously, the author investigated different VR applications to identify relevant interactions. The findings gathered throughout the investigation of the game “The Room VR: A Dark matter” are summarized in Table 1. Similar tables were created for each tested application. However, it should be noted that interactions can be realized in many ways. This means that the implementations are just examples and the same kind of interaction (e.g., reading a letter) can be very different in other applications.

At the start of the game, the user was first confronted with the display of a few tooltips. These intended to explain basic controls. Shortly after that, the user had to move to the first interactive object of the virtual environment. Moving around (in this case, teleporting) supported two different tasks: Firstly, it allowed them to *select* their destination and, secondly, to *navigate* through the environment. To do so, they used *gesture language*, communicating their intentions to the machine by pointing toward their destination (therefore using hand and body gestures). Finally, the machine receives the user’s input by having them *push the controller’s joystick forward* and then releasing it. This interaction often reoccurred, yet the distance between the user and object (referring to the possible destinations as interactive objects) always exceeded the personal space, therefore, making this interaction less relevant for the test. However, this example already shows how the communication between humans and machines is not fully developed yet. After all, this teleporting could, for example, also be implemented by keeping track of the user’s gaze direction. While the human agent already provides this information, even modern-day VR systems seldom offer modalities/channels to process it. As a result, it is always important to not just analyze what information is transmitted to the machine, but also if and how it is processed.

However, the first interaction within the personal space happened rapidly after that, when the users had to gather some information about the story of the game by interacting with a projector. This interaction consisted of two parts: The users could *manipulate* the lever of the projector (grabbing it to pull it down) which allowed them to *edit the environment* as it changed the contents displayed by the projector. This was the effect of using gesture language and more specifically of them using the grab and release functionalities of the controller, resulting in interaction within the personal space. The second part, however, considered identifying the contents displayed by the projector. This occured at a larger distance and therefore outside the personal space. This example further illustrates the difference between different interaction tasks, in this case between manipulating the VE and editing it. Manipulation refers to temporarily rotating, scaling, or moving a single object. In contrast to that, editing the environment means that the user made lasting changes to the environment, in this case, they edited the environment to change the information displayed on the projector by manipulating the position of the lever. Furthermore, it also shows the previously mentioned scope-relation of interactions. While interacting with the projector and reading the displayed information could be seen as one loop, it could also be split up again to isolate the interaction with the lever or that of reading the information from one another.

Looking at the other examples from this application reveals more on the way interactions are implemented in this application. While there are different interaction tasks throughout the different examples, they mostly share the same interaction technique, listen to similar events, and rely heavily on the controller as an input device. As stated by L. Oviat, most human input in VEs is currently achieved through gesture-controlled-input devices. These devices are easy to use and mostly intuitive, yet they cannot provide a fluent dialogue between the machine and the user. According to her, integrating multiple input modalities for the user would achieve a higher level of interactivity while also increasing the naturalness of the human-VE interface (Oviat 2009). While some headsets, like the HP Reverb G2, offer ways to measure gaze direction or record voice commands through microphones, most applications, like the one used as an example here, still rely mostly or even exclusively on controllers as input devices.

The previous examples revealed how the layered model can be applied to analyze applications and the interactions they include. It further allowed differentiating the interactions while also providing insights into their similarities. However, the two goals of investigating these interactions were achieved. On the one side, it is now possible to distinguish different interactions within the applications based on the loop they represent. On the other side, assessing the distance between objects and the users' eyes allows assuming their relevance to this specific research. The relevance of this distance will be further explored in the next chapters on visual discomfort. Summarizing this chapter, it can be said that a clear picture of all interactions used in an application is important to understand how users interact with the environment while also widening the view of possible improvements, like the implementation of multimodal inputs.

Interaction name	Interaction tasks	Interaction techniques	Events	Input devices	User-object distance
Projector	Manipulation, VE editing, identification	Gesture language	Hand/body gestures	Controller (Grabbing, releasing)	~ 50-70 cm using the lever. (Within personal space, arms often extended to the max range) - Outside of personal space when reading through presented cues)
Teleporting/ moving around	Navigation, selection	Gesture language	Hand/body gestures	Controller (Joystick)	Outside of personal space (based on target)
Reading a letter	Identification, manipulation	Gesture language	Hand/body gestures	Controller (Grabbing, releasing)	~ 40-60cm (Within personal space, arms moderately extended)
Open the safe	Manipulation, VE editing, selection	Gesture language, 3D menu	Hand/body gestures, button click	Controller (Grabbing, releasing, pointing)	~ 40-60cm (Within personal space, arms moderately extended)
Retrieve an item from the evidence	Manipulation, VE editing, identification	Gesture language	Hand/body gestures	Controller (Grabbing, releasing)	~ 40-60cm (Within personal space, arms moderately extended)
Open small box	Manipulation	Gesture language	Hand/body gestures	Controller (Grabbing, releasing)	~ 50-70 cm (Within personal space, arms often extended to the max range)
Activate special lens	Manipulation, selection	Gesture language, 3D menu	Hand/body gestures	Controller (Grabbing, releasing, pointing)	~ 40-60cm (Within personal space, arms moderately extended)

Open a large mysterious box	Manipulation, VE editing, selection	Gesture language	Hand/body gestures, button click	Controller (Grabbing, releasing, pointing)	~ 50-70 cm (Within personal space, arms often extended to the max range)

Table 1: Applying the layered model for interactions in VE to the game "The Room VR: A Dark Matter"

2.3 The VA conflict as a cause for visual discomfort in VR

This chapter aims to explain why the vergence-accommodation conflict occurs in HMDs. First, it will provide an understanding of the differences between motion sickness and visual discomfort. Following that, the author will explain the causes of the VA conflict in HMDs and how it affects visual discomfort. Based on these observations, the author will then create a concept for a user test that aims to prove the influence of this conflict during interactions within the personal space in VR.

2.3.1 The differences between motion sickness and visual discomfort

As mentioned previously, one core goal of this work is to better understand the occurrence of certain symptoms of visual discomfort in modern VR headsets. However, to achieve that, it is important to have a clear picture of what visual discomfort means and how it differs from the famous term "motion sickness". In this chapter, the author will define both terms and compare them on the basis of their causes and symptoms.

When we talk about motion sickness, it is very important to know that while this topic is very important to the development of VR technologies, it is not restricted to this field of research. The wide variety of occurrences of motion sickness has led to several terms being used instead. When searching through the literature, one will notice variations like "cybersickness", "VR sickness" (Chang et al. 2020, S. 1658), "space motion sickness", or "simulator sickness" (Stanney 2002, S. 637). This variety of terms relates to the circumstance that motion sickness can occur in many different situations, including such that we encounter daily like driving in a vehicle or more specific ones like the use of VR headsets. Cybersickness, for example, is often used in scenarios that focus on VR technologies. As defined by Burdea "Cybersickness is a form of motion sickness that results from interaction with or immersion in virtual environments. Its main symptoms are eye strain, disorientation, postural instability, sweating, pallor, drowsiness, nausea and (in rare cases) vomiting” (Burdea 2003, S. 269).

Another factor contributing to the variety of terms is the number of theories referring to the cause of motion sickness. Currently, there are 3 widely accepted theories, yet these theories should not be understood as ruling out one another but instead providing several possible causes, oftentimes linked to or based on factors suggested by the other theories. Firstly, the sensory conflict theory suggests that motion sickness “may result when the environment is altered in such a way that incoming information across sensory modalities (primarily visual and vestibular) are not compatible with each other and do not match our mental model of expectations” (Jerald 2015, S. 165). A practical example of this would be a VR rollercoaster, which stimulates the visual sensory system (the eyes) in a way that we believe that we are moving. Yet our vestibular sensory systems (our balance organs) are only stimulated by “real” movements, therefore suggesting that we are not moving or at least not as much or differently. This leads to a conflict between both inputs and thus to motion sickness.

The second theory is called the evolutionary theory and was proposed by M. Treisman. It suggests that motion sickness might be caused as an accidental byproduct of our evolution. He suggests that certain types of motion or disturbances in sensory input or motor control are naturally attributed to the ingestion of toxins. As a reaction, our body produces a variety of symptoms targeted to rid the individual of ingested neurotoxins (Treisman 1977). According to this theory, our evolution has taught our brain that mismatches in our perception are mostly caused by intoxication. Like consuming alcohol or other poisonous substances, our body reacts with defensive mechanisms. The only difference is that in this case, our brain is wrong.

Riccio and Stoffregen proposed the third and last theory, which is called the “postural stability theory”. They suggested that the exposure and duration of postural instability is the key factor determining the severity of motion sickness. According to them, an animal will always try to achieve a stable posture. If disturbances in our perception hinder us to do so and especially if that happens repeatedly or for prolonged amounts of time, we will experience motion sickness (Riccio und Stoffregen 1991, S. 205–206). According to their theory, motion sickness is a result of our bodies trying to keep our postures stable. If that is not possible, they react through motion sickness symptoms. The feeling of nausea, headaches, or fatigue will automatically lead to us lying or sitting down, closing our eyes, or other steps to help us stabilize thus achieving postural stability again.

The relevance of motion sickness persisted throughout decades of VR-related research. As stated by D. Harm, “Motion sickness induced by exposure to virtual environments may be a key factor in limiting widespread use of virtual environment technology. As many as 30% of individuals exposed to virtual environment systems have symptoms severe enough to discontinue use” (Stanney 2002, S. 655). While the results of studies with more recent VR technologies show better results, the problem itself remains. Summarizing, it can be said that while the theories represent different approaches, all of them argue that motion sickness is caused when our senses conflict with one another or oppose natural conditions. Concluding, this work will refer to motion sickness as *a physiological response of our body to misalignment between expected inputs from our sensory organs and cues presented by the virtual reality system. As a result, we experience different disease-like symptoms which aim to fix naturally occurring causes, e.g., ridding the body of toxins*. The Simulator Sickness Questionnaire (SSQ) which will be used in the test and described later in detail contains a list of these symptoms. They are based on a wider range of symptoms reevaluated in the context of using modern-day simulators.

As mentioned previously, many symptoms caused during the use of VR can be attributed to motion sickness and while this represents a good reason for the focus on reducing it, it is also a reason for the topic of this work. As stated before, all these symptoms may indicate motion sickness, yet they are not guaranteed to be caused by it. Many symptoms might also have other reasons, like visual discomfort. While this sounds like a symptom itself, it instead describes a group of such, namely those that are related to our human visual apparatus - our eyes. It is part of so-called Asthenopia or commonly “weak-eye” and represents the subjective assessment of it, e.g., the feelings of eyestrain, eye dryness, or nausea. As such it stands in contrast to visual fatigue which describes the objectively assessable symptoms and "can be measured by means of objective parameters such as eye dryness, eye accommodation, etc." (Mackay 2013, S. 308). Figure 10 shows the two parts and was taken from Mackay.

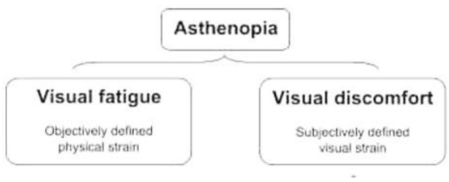

Figure 10: The two parts of asthenopia (Mackay 2013, S. 308)

Since many of the symptoms attributed to visual discomfort align with those of motion sickness, many often assume it to be the same or at least similar. Yet the difference can be found in the causes for both. As described earlier, motion sickness occurs as a response to conflicts between multiple sensory inputs. Visual discomfort however is a result of fatigue caused by processes within visual apparatus, beginning with the reception of a clear image in our eyes and reaching up to the processing of transmitted images within our brain. As a result, it only represents conflicts and issues within one sensory system, the visual system. As Mackay explained, there are several causes for visual discomfort, like "excessive screen disparity of the two instances of the image on the screen; perceptual inconsistencies (e.g. seeing an object as closer than the screen, but falling outside its frame); screen point of view and age-related eye physiology, technology-based stereoscopic distortions" (Mackay 2013, S. 309). However, as he points out, the cause mainly contributing to the severity of visual discomfort is the vergence-accommodation conflict, which will be explained in the next chapter.

In concluding this chapter, a few important learnings should be acknowledged. Firstly, while motion sickness and visual discomfort share a large portion of their symptomatology, they are very different in their causes. Secondly, these different causes represent possibilities to create tests in which one effect could be isolated from the other. The best way to achieve this is by minimizing the causes for one effect, e.g., motion sickness, while maximizing the causes for the other, in this case, visual discomfort. Lastly, because of these different causes, different approaches are necessary to reduce them.

2.3.2 The Vergence-Accommodation-Conflict

As mentioned previously, this investigation will focus on the vergence-accommodation conflict for two reasons. Firstly, because it is a basic problem of every stereoscopic display system, and secondly, because many studies have found that visual discomfort and fatigue can often be attributed to this conflict (Shibata et al. 2011, S. 1–2).

In the past, scientists were able to identify numerous different causes of visual discomfort when viewing stereo displays such as discomfort due to the eyewear required to separate the two eyes' images, ghosting or crosstalk between the two images, misalignment of the images, inappropriate head orientation, vergence–accommodation conflict, and many more. Oftentimes these causes relate to misalignment between the conditions we are used to viewing reality in contrast to how environments are displayed on such displays (Kooi und Toet 2004, S. 99–108).

To understand the VA conflict, it is first necessary to understand how our eyes adjust to project sharp images of visible contents. As the name of the conflict suggests, this includes accommodating the refractive power of our eye lenses to the distance of the object while converging the angle of our eyes to meet the distance of the object.

In more detail, accommodation describes how our eyes adapt the refraction of our lenses to the distance of a given fixation point. This means that when we look at a nearby object the ciliary muscles tighten while the zonular fibers relax, resulting in a thicker lens, which breaks the incoming light rays at a sharper angle to fixate them on our retina. However, when fixating on a distant object instead, the ciliary muscles relax while the zonular fibers tighten, thus flattening the lens and resulting in lower refractive power (Hottong et al. 2019, S. 2–3).

The vergence of our eyes on the other side describes the angle to which our eyes must turn to focus on an object at a certain distance. Thus, when looking at close objects, both eyes must converge depending on the object's position. Based on the severity of each eye's muscles strain, the brain can deduct the distance of an object (Junling 2022). Figure 11 shows how both the vergence and the accommodation change for close and distant objects.

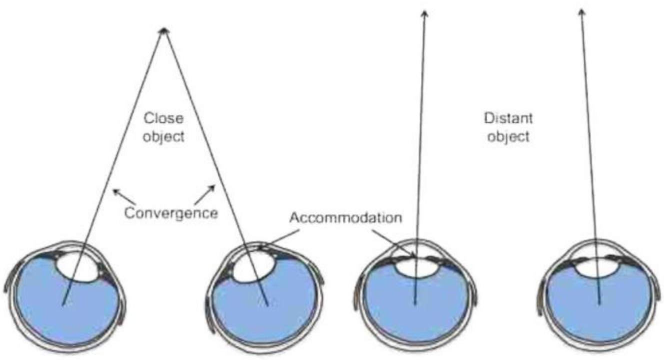

Figure 11: Vergence and Accommodation for close-up and distant objects. (Junling 2022)

Figure 12, presented below, was taken from T. Shibata's article in the Journal of Vision from 2011 and shows why modern stereo 3D displays cause a conflict between vergence and accommodation. The first column (N) shows viewing conditions in natural conditions while columns 2 and 3 show scenarios where factors like the use of glasses (G), or the view of stereo

3D imagery (S) alter the conditions. Under natural conditions, vergence and focal distance behave equally. As a result, both responses to the position of an object are neuronally coupled, leading to an increased response speed. While we can ignore the middle column for this study, the third column shows the cause of conflict in HMDs. Under these viewing conditions, the focal distance is always accommodated to the distance of the display. However, the eyes of the recipient will converge to the simulated position of the content (Shibata et al. 2011, S. 2–3). Thus, the neural link between both responses must be overwritten by our brain to get a sharp image. This process of uncoupling both responses in return causes symptoms like eyestrain, headaches, and visual fatigue (Hoffman et al. 2008).

In the next chapter, the author will present a concept for a test that aims to prove the influence of interactions in the personal space in VR systems. The previous chapter provided an in-depth analysis of the surrounding architecture of such systems and was based on research throughout the literature.

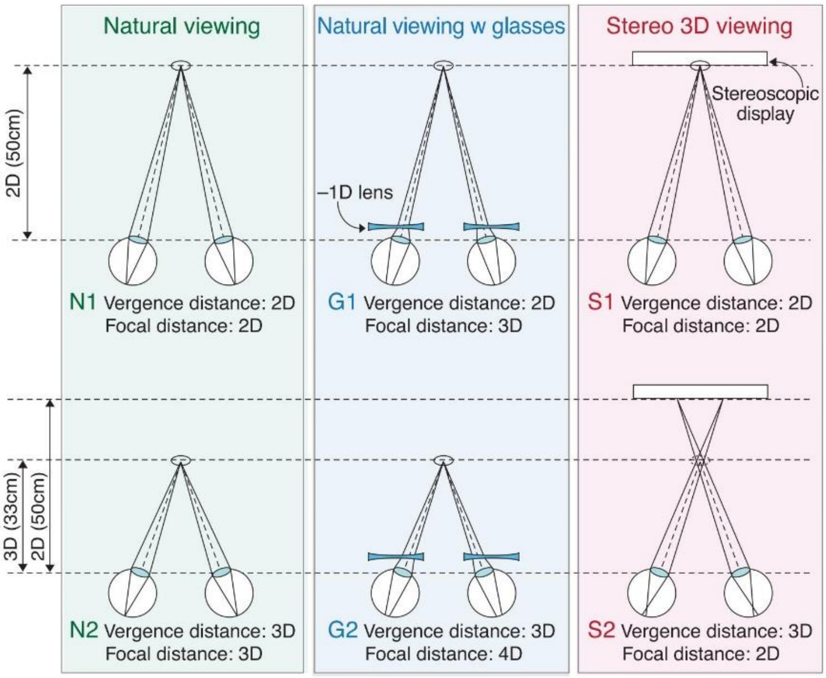

Figure 12: The vergence-accommodation conflict is caused due to a conflict between natural viewing conditions (column "N") and stereo 3D viewing conditions (column "S"). (Shibata et al. 2011, S. 2)

3 Methodology

In this chapter, the author will provide a detailed description of the user test. The author will start by creating a framework for the test to describe the parameters for the target audience. Continuing, relevant research questions will be explained. Followed by that, the author will provide insights on the used methods and lastly provide information on the preparation of this specific instance of testing as well as its execution.

3.1 Test Framework

Creating a framework for the intended user tests aims to guarantee the quality as well as the integrity of all collected data. As such, its foundation is based on the core subject of this investigation. The previously discussed VA conflict presents an issue to modern-day HMDs and resolving or reducing it could help to improve future VR experiences. Furthermore, identifying factors that can increase or decrease the severity of this conflict could help adjust current and future applications to improve them in many ways.

As a result, the subject of this investigation is to **find evidence for the influence of interactions in the personal space in VR on visual discomfort**, more specifically the vergence-accommodation conflict (VAC).

Following this, it is important to look at the target audience members and define their characteristics accordingly. This will help to find fitting participants more easily and allow us to compare the gathered information. The following list gives an overview of the gathered characteristics:

- **Gender:** The group of participants should represent equal parts of the gender spectrum. This is important to ensure that the final test results are appropriate for statistical analysis.
- **Age:** This is relevant as older people tend to lose their ability to accommodate. In fact, by their mid-fifties, most people have lost that ability completely (Koulieris et al. 2017, S. 3). As a result, the test should be performed on people that are significantly younger than that. Yet, to ensure that the participants can give proper feedback and can sign

the consent form, they should be at least 18 years old. Thus, participants under the age of 18 and above the age of 40 are not suited for the test.

- **VR-Experience:** As mentioned in the chapter on the vergence-accommodation conflict, the symptoms caused by that conflict are a result of the neural uncoupling of both responses. This uncoupling can be trained by using HMDs regularly, leading to a decreased severity of these symptoms. As a result, the target audience should consist mostly of less experienced VR users. Still, it would do well to have a few more experienced users, as it would allow us to see if more experience indeed leads to a lesser severity of the VA conflict.
- **Users of glasses/optical correction devices:** As shown in the Figure from Shibata in the chapter on the VA conflict, a wearer of optical corrections is influenced by an alteration of natural viewing conditions. As such, they might be affected differently by the influences of the VA conflict. Due to this, it is important to differentiate between both. As a result, wearers of glasses or other optical correction devices will be excluded from the main group of participants. However, as a separate group of participants, they could reveal more about the influence of such devices on the severity of the VA conflict.
- **Distance between eyes:** Nowadays, most HMDs offer ways to adjust the distance between both lenses to the individual distance between the eyes of a user. This is important as the lenses must be centered in front of the eyes. If that is not the case, the user will not have a clear vision. Therefore, it must be certain that the participant's eye distance does not exceed the possible adjustment of the lenses of the device. In this test, the participants will use the HP Reverb G2, which lenses can be adjusted between an eye distance of 60 mm up to 68 mm.
- **The ability to see stereoscopic:** As HMDs require the recipient to see stereoscopic images, it must be ensured that they possess the ability to do so. This is achieved by completing the so-called Randot-Test in which the stereo visual acuity of the volunteers is determined by 10 Randot stereo images. Each image contains 3 circles, of which one is stereoscopically separated from the background. The results of this test allow a judgment of the participant's stereoscopic ability.

Based on these characteristics, the author will later design a pre-test that will help to find participants and categorize their results from the main test.

3.2 Objectives and research questions

As mentioned before, this test focuses on results regarding the visual discomfort of users after being exposed to interactions in the personal space in VR. When viewed from a UX angle, this research studies the aspects of inclusivity and safety. It aims to reduce health risks while allowing more people to access VR comfortably (limiting/eliminating visual discomfort). Thus, this test has two main research questions:

- **Does the use of interactions in the personal space in VR impact visual discomfort?**
- **If yes, is it possible to identify certain interactions that influence this visual discomfort more than others?**

To answer these research questions, the author will use a set of methods and by that aim to collect a larger amount of information while also reducing or avoiding the downsides of the individual methods. For this investigation namely two methods were chosen: **Playtesting** preceded and followed by the answering of a **Questionnaire**.

3.2.1 Playtesting

Playtesting is a very user-orientated research method, as it consists of creating a prototype and analyzing how the participants from a chosen audience react to it. It can happen through quantitative feedback like documenting the number of errors done when trying to complete a certain task, or qualitative feedback like participants opinions on different parts of the tested subject. This method is heavily used within the gaming industry and usually focuses on the iterative improvement of applications by gathering user feedback on desired topics and using them, in turn, to improve on the previous iteration (Quinn et al. 2013, S. 222).

The good thing about this method is that it is very flexible and can be used for almost any research question. The only necessary thing is something that can be tested. However, to be able to conclude proper results from it, it is important to adjust the presented prototype to the UX aspect that the conductor desires feedback on (Choi et al. 2016, S. 254).

Since playtesting itself is a considerably basic research method, the desired feedback can often be improved by adding other methods like "Thinking out loud" or surveys/questionnaires/ interviews to the test. Thinking out loud helps to understand why a user might have made certain errors, while questionnaires help to go more into depth when it comes to the participants' opinions after playing the prototype.

In this user test, the users will be presented with a scenario in which they will often use interactions in the personal space. The prototype should include several different interactions, e.g., reading, writing, or altering objects (like loading a gun). Furthermore, the breaks between these interactions should be relatively short. This should help to show more significant results due to exposing the users to a more extreme scenario. However, to avoid the occurrence of motion sickness, the users will be asked to remain seated throughout the session. Furthermore, the game used as the test object, namely “The Room VR: A Dark Matter”, includes several functionalities that aim to reduce motion sickness. This includes steady positions between which the user must teleport, an environment with overall little movement, and fade-in/-outs when rotating or teleporting. While performing the test, the user will also be asked to express their feelings in a “Thinking out loud” approach. As a result, this part of the test is aimed to give a basic understanding of the influence of these interactions on visual discomfort by showing the difference in the user’s perception between pre- and post-exposure. Additionally, the thinking-out-loud approach documents the feelings of the users and uses them to differentiate the influence of the different interactions on the results.

3.2.2 Simulator-Sickness-Questionnaire

In general, questionnaires are especially helpful when it comes to analyzing the opinion of the participants and how they view different parts of the product. One of the advantages of this method is that it allows the conductor through the choice of questions to decide what things they will get feedback on. Another advantage that relates to this choice of questions is that the results are easily measurable since all participants answer the same questions. Questionnaires are also very efficient when it comes to resources (mostly money and time) that must be spent to collect data. It is also easy to gather large amounts of data and deliver quick results (Doane 2015).

But the scalability and the measurability come at their price. To maintain this measurability, questionnaires are inflexible, meaning you cannot change anything about the survey once you have started to administer it. Another point is that the results are often influenced by the perception of the participants, which can be helpful as the goal is to collect their feedback but might have a negative influence if the participants give answers that do not fit what they want to say (due to social influences, like feeling obliged to say certain things). This is a reason why questionnaires are not fitted for controversial issues, as the socially biased influence becomes much more important. Lastly, questionnaires often have the problem of being somewhat blind to certain topics, that might have been interesting for analyzing purposes but were left out due to the creator of the questionnaire missing to ask related questions. (Doane 2015)

The Simulator-Sickness-Questionnaire (SSQ) is based on the Pensacola Motion Sickness Questionnaire (MSQ). The SSQ was designed as a result to accommodate the need for a specific questionnaire that would target motion sickness induced by simulators. In contrast to its predecessor, the SSQ reevaluated the symptoms listed in MSQ and filtered them for their significance in modern-day simulators. A core issue of the MSQ was that while many symptoms of simulator sickness are like those of motion sickness, many of them are less severe and affect a smaller part of the population. As a result of the filtering process, the SSQ only includes 16 symptoms that were identified to be relevant for simulator sickness studies (Kennedy et al. 1993, S. 204–205). Therefore, the user must fill out the questionnaire twice, once before and after the test. In doing so, it is possible to compare the results pre- and post-exposure, thus showing changes that happened during exposure. In the SSQ, the user is asked whether they are experiencing several symptoms associated with motion sickness in simulators. The list consists of 16 symptoms, for each of which the user can indicate its current severity. The severity is described in 4 levels: 0 (not affected) – 1 (slightly affected) – 2 (moderately affected) – 3 (severely affected). After collecting the results from every participant, the authors of the test design suggested the application of a scoring system. A detailed description of the development of that scoring system can be found in the original SSQ design (Kennedy et al. 1993, S. 207–208). Most importantly, it should be noted, that they decided to split the symptoms into 3 categories: Nausea (N), Oculomotor (O), and Disorientation (D). Ultimately, they developed a computation matrix, that allowed to calculate an unweighted sub score for each category. Multiplying these sub scores afterward with their respective weight factor would deliver weighted sub scores that would allow for easier comparison, while adding the sub scores and multiplying the result with an overall weighting factor would deliver a total simulator sickness score. The matrix as well as these factors are displayed in Figure 13.

While the previously suggested categories also include one, namely the oculomotor category, that aligns largely with the symptoms of visual discomfort, it does not align perfectly. Furthermore, it should be mentioned that Kennedy et al. developed the scoring system as well as the categories, aiming to compare the occurrences of simulator sickness of each participant. While they also proposed an alternative way by providing general factors for each symptom regardless of the previously suggested categories, these calculations do not seem reliable for the context of this test. This has mainly 2 reasons. On the one hand, they also state that their sample size consisted of more than 1100 observations and while the factors are equated for this sample size, the midpoints (meaning the factors for smaller sample sizes) are not equal (Kennedy et al. 1993, S. 213). As this works' sample size will be significantly smaller (between 15 and 20 participants) one cannot expect that such specific factors will still be matching. On the other hand, these factors aim to yield results that help to compare simulator sickness of different participants. This does not align with the focus of this work.

Computation of SSQ Scores

	Weight		
SSQ Symptom[a]	*N*	*O*	*D*
General discomfort	1	1	
Fatigue		1	
Headache		1	
Eyestrain		1	
Difficulty focusing		1	1
Increased salivation	1		
Sweating	1		
Nausea	1		1
Difficulty concentrating	1	1	
Fullness of head			1
Blurred vision		1	1
Dizzy (eyes open)			1
Dizzy (eyes closed)			1
Vertigo			1
Stomach awareness	1		
Burping	1		
Total[b]	[1]	[2]	[3]

Score
$N = [1] \times 9.54$
$O = [2] \times 7.58$
$D = [3] \times 13.92$
$TS^{c} = [1] + [2] + [3] \times 3.74$

[a]Scored 0, 1, 2, 3. [b]Sum obtained by adding symptom scores. Omitted scores are zero. [c]Total Score.

Figure 13: Computation Matrix of SSQ Scores (Kennedy et al. 1993, S. 212)

Focusing on the topic of this work and as a result from the observed similarities and differences between the original study on which the SSQ was based and the study done in this work, it can be said that while these symptoms are viewed as symptoms of motion sickness in the SSQ, it is still usable in the context of this work. As the symptoms of visual discomfort (eyestrain, nausea, difficulties focusing, blurry vision, headaches, and fatigue) are also associated with motion sickness they are also included in the SSQ. This shared symptomatology can make it hard to distinguish the causes of them, yet by designing the experience as indicated earlier in chapter 2.3.1 it can also help to show that the symptoms indicate visual discomfort and not motion sickness if only the specific symptoms of visual discomfort increase during the test while the ones that are unique to motion sickness remain mostly the same. However, in contrast to the original study and based on the scope of this work's study, no weight factors will be applied to the results from the questionnaire. Instead, the symptoms will be split into two categories. One category will include all symptoms included from the questionnaire that are also symptoms of visual discomfort (eyestrain, difficulties focusing, blurry vision, and headaches). The other category will include all symptoms that are exclusive to simulator sickness. The two categories can then be compared based on their unweighted values, both per participant and on average. Yet, as a perspective for future tests it can already be noted that a similar approach could be taken, to ultimately design a questionnaire that would allow to detail the occurrence of visual discomfort in contrast to that of simulator sickness by using weighted factors calculated specifically for this issue.

One will further notice that fatigue was not counted as a symptom of visual discomfort. As the execution of multiple test runs predating the start of this study showed, many participants seemed to interpret fatigue as a symptom that affected the whole body, which is not wrong. However, this interpretation deviates much from the symptom of *visual* fatigue. Due to the vagueness of the fatigue included in the questionnaire, it will not be counted as a symptom of visual discomfort.

Before answering the SSQ, the users will also be asked to provide information on their age as well as their experience with HMD. This information might be relevant as the research so far has shown that both factors can play a role in the severity of visual discomfort symptoms. This questionnaire is expected to deliver easily understandable results, especially regarding the first research questions. However, the second question can hardly be answered with the results from the questionnaire as it only shows how the comfortability of the user changed, not when.

3.3 Test Preparation

Based on the gathered information, this chapter aims to explain the final design and execution of the planned user test.

As a first step, it was important to find a suitable application that could be used as a test subject. While searching for such applications, the author specifically filtered for certain properties. To qualify, an application had to make extensive use of interactions within the personal space and, additionally, use a variety of those. This filtering process led to the choice between these three applications:

- **Half-Life: Alyx** is a virtual reality first-person shooter game developed and published by Valve in 2020 (SteamVR - Valve Corporation 2023). The game is famed for its well-designed environment and overall VR experience.
- **EON-XR** is a platform that combines several tools to help "educators, trainers, employers, and other users [...] to create interactive and immersive AR and VR lessons without needing any coding or advanced technological knowledge" (EON Reality 2021).
- **The Room VR: A Dark Matter** is a virtual reality escape room game that was developed by Fireproof Games and released in 2020. The game is a mix of different puzzles that have to be solved while progressing through the game (Fireproof Studios 2022).

After testing these applications and considering their advantages and disadvantages, the author ultimately designated the third option and specifically its tutorial level as the test subject. Testing it revealed that this game offers many different interactions within the personal space, while also forcing the players to interact for extended periods. Through this, the game can create many instances of the VA conflict and thus a scenario that should yield more significant results. Additionally, choosing a tutorial level meant that it was easy for new players to understand everything easily and quickly, which was important to keep the user test relatively short. Furthermore, it was also a good way to make sure that all controls are properly introduced as they are being explained along the way. Lastly, the game itself is very easy to install and makes use of different optimizations that help reduce motion sickness induced through player movement, like teleporting instead of moving freely or fading in and out quickly when the player rotates via using of the controller’s joystick. These optimizations are important since the goal of this test is to provoke visual discomfort while eliminating motion sickness (based on the learnings from the chapter “The differences between motion sickness and visual discomfort”).

Taking a closer look at the tutorial level and based on the models proposed in chapter "2.2 Interactions" the author distinguished 6 different interaction scenarios or otherwise called stations (referring to them as a stopping point along the way of progressing through the level). These scenarios represent different situations within the level, in each of which the user must interact with a certain object more extensively. The following list is based on the table presented in chapter "2.2.2 Interactions in the personal space" and should give an overview of these scenarios/stations:

- In **Station 1** the users interacted with a projector. By pulling down a lever on its side, they could switch through the different slides which showed different pieces of information on the criminal case. Thus, this station included the interaction tasks of *manipulating* the lever and therefore *editing* the virtual environment (as the projected slides changed). Furthermore, it also included the task of *identification,* as the users had to identify the information presented on the slides to use them later in the game.
- Continuing to **Station 2**, the users had to read a letter. As such, it included the interaction tasks of *identification* (which relates to the actual process of reading) and *manipulation* (as they could pick up the letter and move it around). However, in contrast to the first Station, it did not involve VE editing, since the letter went back to its original position, once released by the user. Therefore, in this case, they did not make any permanent changes to the environment and thus did not edit it. After reading the letter, they also had to pick up a key which meant *identifying* where it was hidden and then picking it up, thus *manipulating* it.
- **Station 3** had the users trying to open a safe in their office. Therefore, they had to *select* a key from their inventory and *manipulate* it to plug it into the lock. This would lead to a permanent change to the environment, thus *editing* it, as the key remained in the lock afterward. However, the key would not work, which forces them to continue to station 4 before they could complete this one. Once they had retrieved the item, they could cut the safe open by *selecting* the item from their inventory and placing it onto the safe (*manipulation*). Following that, they had to rearrange some gearwheels (*manipulation*) which would ultimately allow them to open it and retrieve the item in the safe.
- **Station 4** presented the users with a first riddle. As they could not open the safe with the key, they were given the task to check the evidence lockers for a tool that could

help them open it. The station consisted of a blackboard on which different lockers as well as their contents were written down. Though some information was missing as part of the riddle, they head to *identify* the written information and use it to get to the right locker. To check different lockers, the users had to use a control panel, which consisted of two rotatable buttons that allowed them to enter a letter via the first one and a number via the second one. It also included a lever, that when pulled down would open the locker related to the entered code. Therefore, this interaction involved *manipulating* the positions of the lever and the buttons and, since the changes were permanent, *editing* the environment.

- After the users had retrieved the correct item from the evidence lockers and used it to open the safe, they would continue to **Station 5**. The station consisted of two parts. Firstly, they had to read another letter, thus *identifying* its contents, and *manipulating* its position. Users then had to open a small box by rotating the pointer mounted on it in the correct directions. As a result, this part of the interaction also represented the task of *manipulation* (and no editing, as the changes would not stay once the pointer was released). Once opened, they would find a pair of goggles in the box that allowed for a different perspective on the scene.
- Using the found goggles, they would continue to **Station 6**. They had to return to the table from station 2, however, instead of a letter they would now find a larger box on it. To open it, they had to rotate it and *manipulate* it at different points. These changes were permanent, thus involving *editing* of the VE. Finally, after opening the box, they had to *select* the item found in the safe from their inventory and put it onto a socket which would end the tutorial level.

The second step was to create the questionnaires, which were done with Google Forms. Based on the properties mentioned in chapter 3.3.2.1 the author **created a pre-test that gathered the following information:**

1. **Name**
2. **Participant ID (assigned by the test conductor)**
3. **Gender (m/f/d)**
4. **Age**

5. **Number of VR experiences within the past 6 months (choose one from: “Never” – “Once” – “Less than 5 times” – “Less than 15 times” – “Regularly”)**
6. **Whether the person has any optical impairments (Answers: yes/no)**
7. **Distance between eyes in millimeters**
8. **The Randot test results (integer value between 1 and 10 depending on the test result)**

As mentioned previously, this pre-test aimed to keep the results comparable and to prevent certain sources of problems and their influences on the outcome. As a result, the pre-test helped to reveal if a participant would qualify for the main test or not. This decision was based on their answers to questions 6 and 7. This meant that only people without any optical impairments and an eye distance of 64 mm +/- 4 mm were allowed to participate in the next step.

Following that, the author used Google Forms to create an instance of the SSQ which mirrored the version proposed by the International Journal of Aviation Psychology (Kennedy et al. 1993). As such, the participants would first state whether they currently experience motion sickness. If so, they would also be asked since when they were experiencing these symptoms. After that, they would be asked to rate the severity of each of the 16 symptoms that are listed in the SSQ.

3.4 Test Execution

While testing, it was very important to repeat the same structure with every participant. This was necessary to ensure that the yielded results share a common base and thus remain comparable. Though the conductor remained the same throughout this series of tests, the following instructions as well as the introduction it mentions will allow reconstructing the test again in the future.

Instructions for the test conductor:

> *“Before starting the test all Covid-19 measures should be taken care of, disinfectants should be ready, and all equipment should be disinfected. Furthermore, the conductor should make sure that the VR headset is set up and the game is started. Once the participant arrives, they will be asked to sit down. The conductor will then read the introduction to them. If there are no additional questions about the testing session,*

they will be given the first SSQ to fill out. Once they are done with that, the conductor will help them to put on the headset and adjust everything to the participant's needs. Following that, the participant will start playing the game. While they are playing, the conductor will write down what the participant is saying. Furthermore, the conductor should actively encourage the participants to give feedback on their well-being. The test should take approximately 15 minutes to complete, and the participant should try to solve most tasks without help. The conductor should only intervene if a participant seems to be stuck on a task or has major issues (like problems with the headset or extreme cases of motion sickness). However, it should be noted that the focus is set on spending as much time as possible in scenarios with interactions in the personal space, not on solving all tasks. To gather further information on this, the conductor will also measure the time spent at each station.

Once the test is completed or the time limit of 15 minutes is exceeded too severely the conductor should help the participant to take off the headset. After that, the participant is handed the second SSQ, which includes the same symptoms. After finishing the test and filling out the questionnaire they should be thanked for their participation."

Introduction for the participant:

"Thank you for coming to this test session. This user test aims to improve the user experience in future VR applications. Please know that you can't do anything wrong during this test, the test is not about your capabilities but those of this application. Everything that you say or do is helpful for this research. Before the test starts, I will give you a consent form. The test will consist of 3 parts: In the first part, you will have to fill out a questionnaire. In the second part, you will play the tutorial level from the game "The Room VR: A Dark Matter" in which you are a handicapped detective in London investigating a mysterious case. You will have to solve several puzzles that include different types of interactions. While playing, you are welcome to think aloud, meaning that you can talk about what you are thinking. This will help me to gather more detailed results. However, unless necessary, I will not answer anything you say or do throughout the test. It should take about 15 minutes to complete the level. Once you have finished the level or the time is up, I will notify you and the test will end.

After that, you will be asked to fill out the Questionnaire another time. Following that the test is over. Do you have any questions so far?"

The test described in this chapter should ideally be executed with at least 30 people. However, due to the strict timeframe of this work, it was decided to limit the testing to a group of at least 16 people. The results yielded from this test will be displayed and discussed in the following chapters.

4 Results

The pre-test and the user test which structures were explained in the previous chapters were executed with a total number of 17 people. The results from these tests will be discussed in this chapter. The author will first discuss results from the pre-test to show details about the group of participants and to see whether the group matched the intended target group. Following that, the author will present the results from the main test. All results will be measured with the help of the observations and findings from the previous chapters.

4.1 Pre-Test results

As stated in chapter "3.3.3.1 Test Framework" designing and executing a test before the main user test worked toward two goals. Firstly, collecting more information on the users would allow for a more detailed analysis of the results from the main test. Secondly, it was important to ensure that all participants of the user test were similarly perceiving VR.

Looking at the results displayed in Figure 14 it can be said, that almost equal amounts of male and female participants took part in the test. Therefore, the goal that was set for an equal representation of genders was achieved, resulting in a split of about 47% female and 53% male participants. However, it should be noted that there were no participants which identified differently from these two genders.

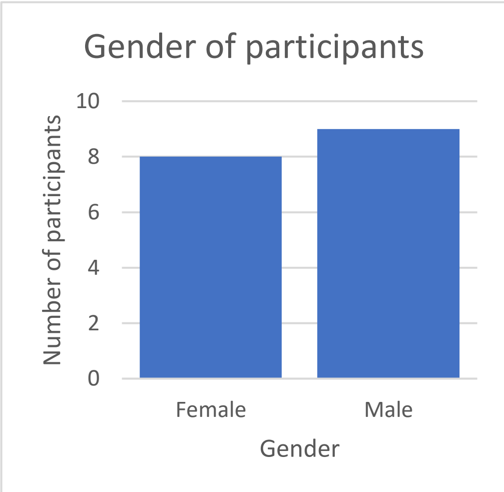

Figure 14: Gender of participants (Source: own representation)

Another limitation of the user target group was related to their age. As stated, the users should be between 18 and 40 years of age. As shown in Figure 15, the age of all participants ranged between 19 and 28 years, with the average participant being 22.7 years old. Following the young age of all participants, two things are important

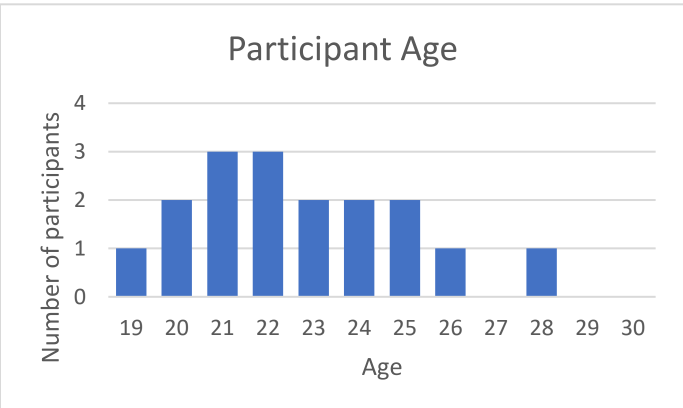

Figure 15: Age of participants (Source: own representation)

to note. Firstly, it might have been good to also have several older participants (between the age of 30 and 40), as they could have served as a comparable group to see more precisely how age affects the results in the main test. However, as it was pointed out in the test design, it is already proven that people lose their ability to accommodate with progressing age. As a result, the young age of the participants allows assuming that all of them are still capable of accommodating properly.

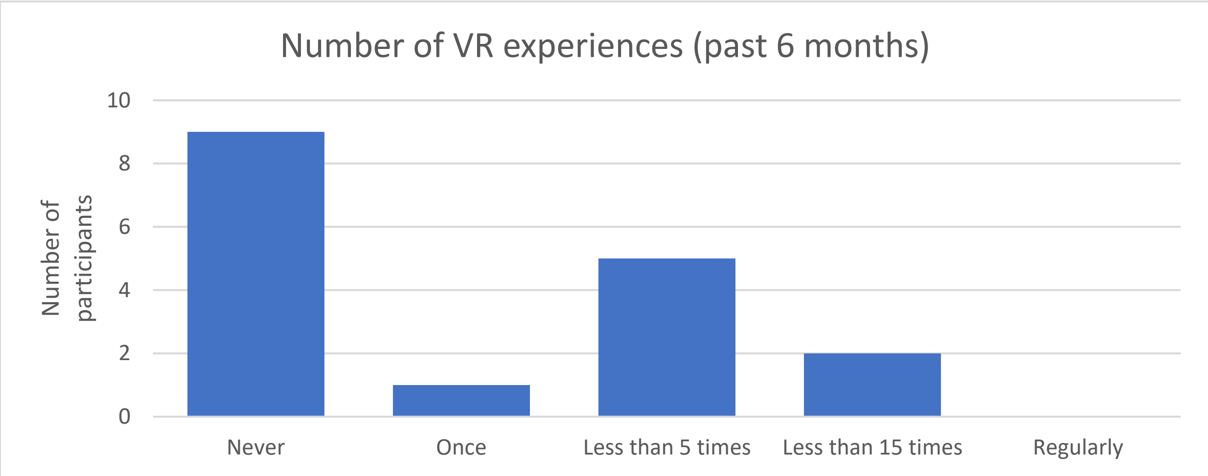

Figure 16: Number of VR experiences within the past 6 months) (Source: own representation)

The next question featured in the pre-test targeted the number of previous VR. The results are shown in Figure 16. Thus, the group of participants aligns with the demands set during the design of the test. Most of the users have either never used a VR headset within the given period or did so less than 5 times. None of the participants have used VR headsets regularly. Therefore, it can be assumed that none of them are used to the VA conflict in VR, meaning that all of them are likely affected by its symptoms.

While these previously mentioned attributes of the participants were meant to see how they align with the target group, the pre-test also included three participant attributes that were more critical to proving whether the participant was suited for the test or not. As mentioned previously, these attributes described whether the participant is a user of any optical correction devices, the distance between their eyes, and the ability to see stereoscopic content (the results from the Randot test). While all participants who are documented in these results proved themselves to be suitable for the test, it should be noted that these three attributes were checked on an even larger basis of participants and only those suitable entered their data. This was done, to keep the amount of the pre-test results equal to that of the main test.

As a result, it can be said that the pre-test was a success and achieved its two goals. On the one hand, it ensured that only participants who fulfilled the criteria were admitted to the main test. On the other hand, it helped to gather additional information on the participating individuals to allow a more detailed analysis of the results from the main test.

4.2 Main Test results

This chapter aims to show the results from the main test, mainly those gathered from the SSQ which was filled out twice by each participant, once before the test and once after it. Furthermore, observations from the test sessions, user feedback, as well as the results from the pre-test, will be used to find possible relations between certain interactions and the occurrence of visual discomfort. It should be noted, however, that the group of 17 participants is too small to draw firm statistical conclusions. The author will first present a general picture, before diving deeper into more specific results.

4.2.1 Station Time analysis

Throughout the sessions, the conductor documented the time of each participant spent at every station. Though the station time alone is only one of many indicators, it will be used later to further analyze the individual results.

Firstly, it can be said that every participant completed the test within the expected timeframe of about 15 minutes. As the boxplot presented in Figure 17 shows, it took them on average 14 minutes and 29 seconds to complete the test (marked with the x-spot) while the middle fifty percent of participants took between 11:47 minutes and 16:30 minutes. The longest session documented took 23:19 minutes, while the shortest one took only 10:11 minutes. Furthermore, the boxplot also shows no outliers, meaning that all participants' session durations can be considered within the expected timeframe. Yet, the longest test duration was more than

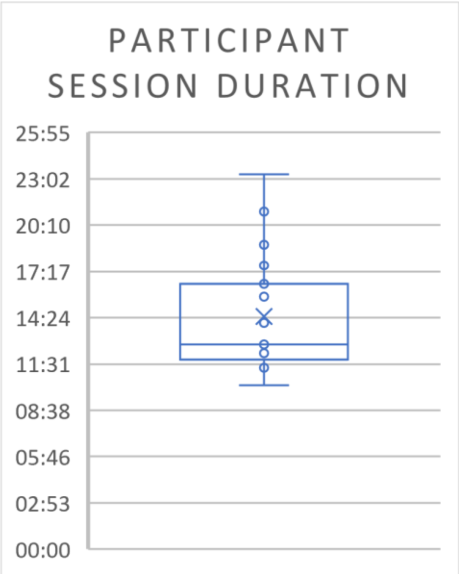

Figure 17: Participant Session Duration (in mm:ss) (Source: own representation)

twice as long as the shortest one. This might play a role later on, as the duration of exposure is expected to influence the severity of symptoms.

However, as mentioned previously, the test conductor also documented the time spent at each station. Figures 18 & 19 show the results of measuring the time duration spend per station. As shown in Figure 18, the completion of station 4 took the users the longest while station 2 took the shortest, which aligns with the fact that station 4 represented a more complex riddle while station 2 consisted mostly of reading a letter. However, Figure 19 gives a more detailed picture of the different station times. It reveals that while the average time of station 4 was the highest, it also had the largest interquartile range (IQR). Its lower quartile is placed at just 02:28 while the upper quartile is at 05:09 resulting in an interquartile range of 02:41. Station 2 in contrast, had the smallest IQR among all stations with just 22 seconds. Yet even the IQR of station 5, which was the second largest among all stations, was just 48 seconds. Looking at the tasks that the users were faced with in each station (as described in chapter "3.3 Test Preparation") reinforces the assumption that station 4 was the most complex one. It presented the users with a complicated riddle, whereas station 2 in contrast consisted mostly of just reading a letter. So, while the reading in station 2 took most participants (ignoring the one outlying value for now) a similar amount of time, the riddle in station 4 on the other hand was often solved very differently by each participant. Some participants for example tried to open several wrong lockers hoping that one of the other

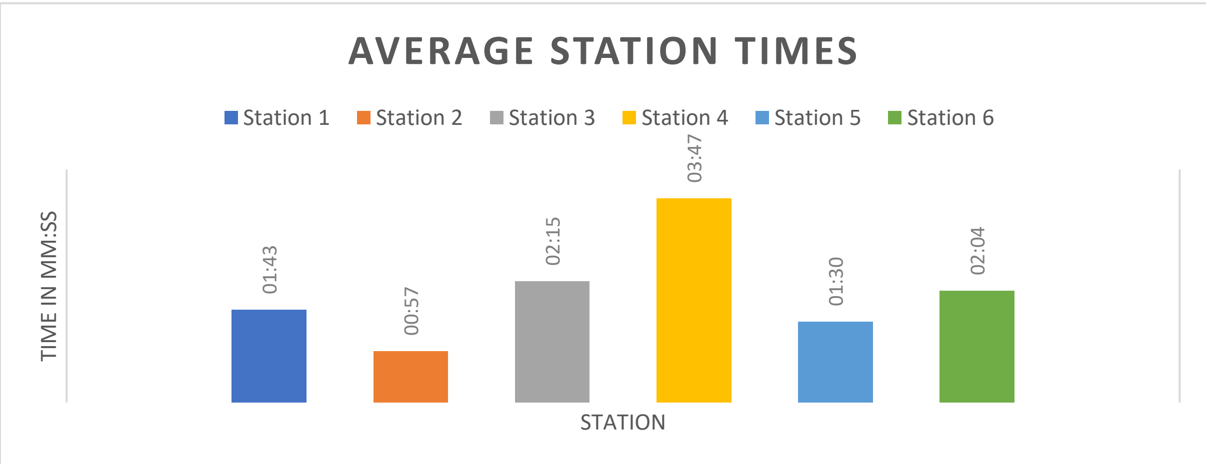

Figure 18: Average time spent per station (Source: own representation)

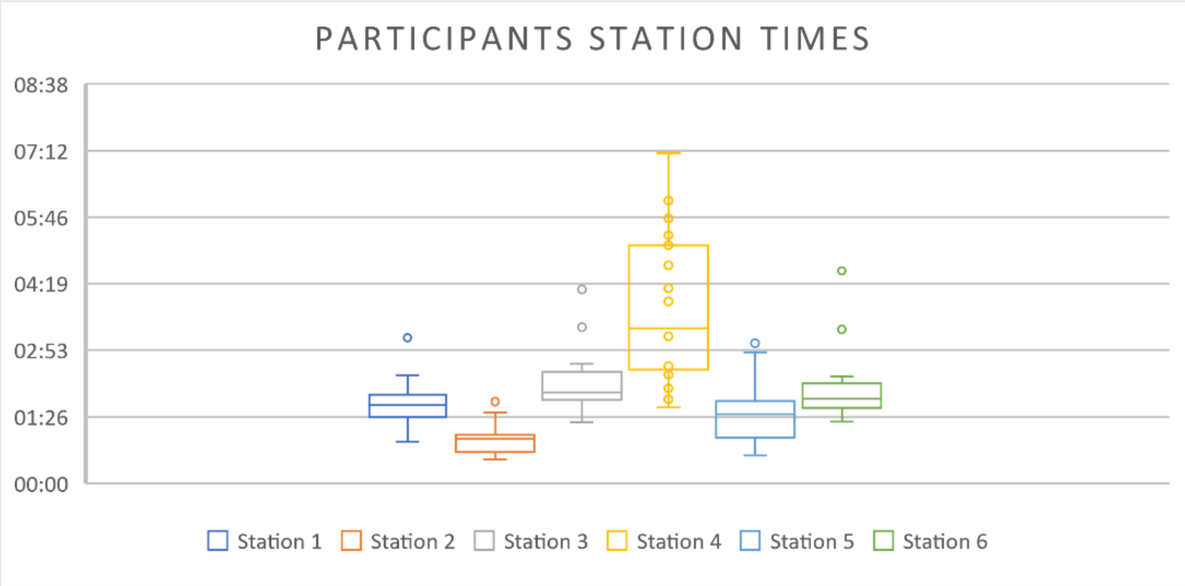

Figure 19: Station Times (represented as a boxplot) (Source: own representation)

items would help them open the safe before understanding that they were meant to find the right locker combination which was not written on the blackboard. Other participants quickly identified it as a riddle, often stating things like, "I remember a similar riddle from the last time I was in an actual escape room.". Similar things happened at Station 5. Again, there were some users who tried to open the box by rotating the pointer quicker and quicker for several seconds before understanding the riddle behind it, while others quickly noticed what they had to do. Another important detail displayed through boxplots are outliers. Such extreme values are present for all stations besides station 4. However, it would not make sense to view these extreme values without further background information, so they will be discussed again later when the individual results are evaluated.

4.2.2 SSQ results

As stated in the concept for the user test, the SSQ is meant to give insights on how motion sickness symptoms change during exposure to VR. It was also explained why the weighting process which was proposed by the original authors would not be suited for analyzing the results of this test. However, it was also discussed that this weighting process aimed to deliver more easily readable results, especially when comparing the simulator sickness of participants. Making use of this, all participants' pre-exposure answers were weighted according to the suggestion of Kennedy et al. to see whether the participants were in a healthy state. Figure 20 reveals that besides one participant, all results can be considered within a comparable range. As a result, the results of this participant were excluded from further analysis as their critical pre-exposure state varies too much from that of the others and indicates that they were physiologically unfit for the experiment.

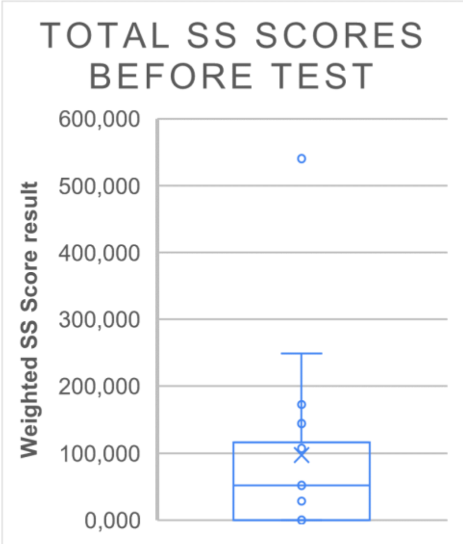

Figure 20: Total Simulator Sickness Scores before Test (Source: own representation)

Moving forward, the hypothesis from chapter 3.2.2 stated that by reducing the possible causes of motion sickness, "the degree to which the symptoms specific to visual discomfort change should (significantly) differ from those exclusive to motion sickness". Figure 21 shows the differences in these changes. The comparison was drawn from the answers to the SSQ. It displays the average of 3 different symptom combinations before and after the test. The first one (blue) took the average of all symptoms included in the questionnaire. The second one (orange) took the average of all symptoms relevant to visual discomfort (headaches, eyestrain, difficulty focusing, nausea and blurred vision) whereas the third one (gray) took the average of the remaining symptoms, therefore those that are exclusive to motion sickness. It should be noted, however, that while visual fatigue is a symptom of visual discomfort, it is not documented through the SSQ. In this case, fatigue describes a general state affecting not just the eyes but the whole body and was also interpreted that way from the participants as they showed through their comments. Therefore, it was not counted among the symptoms of visual discomfort.

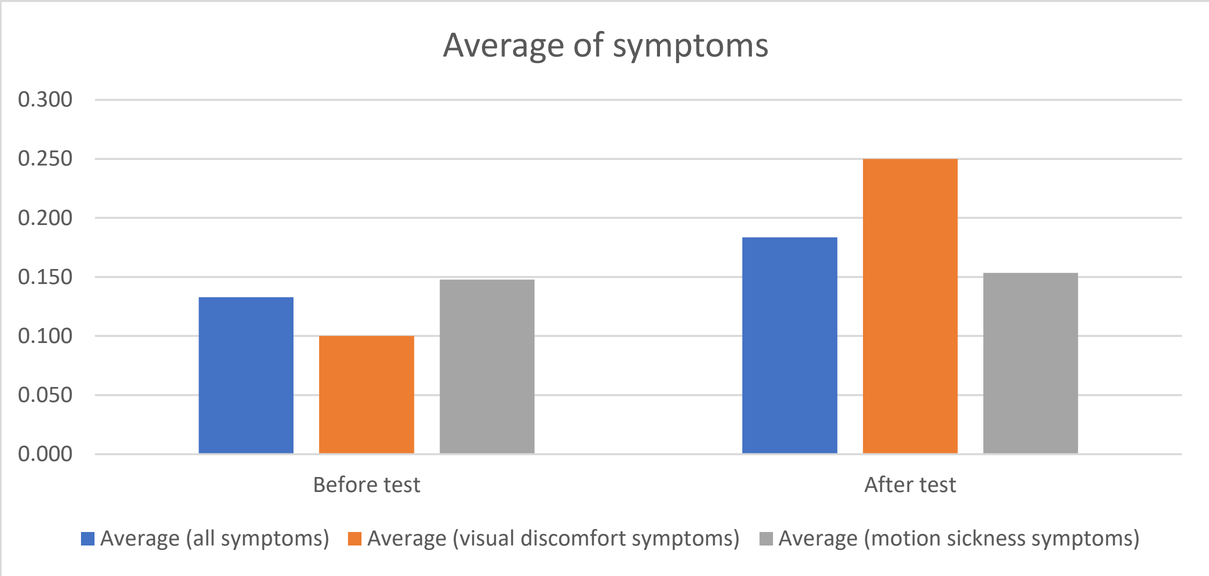

Figure 21: Average severity of symptoms (Source: own representation)

With the help of the presented diagram, the hypothesis stated above can thereby be confirmed. On the one hand, it shows that the symptoms shared between visual discomfort and motion sickness saw a relatively large increase, while the symptoms exclusive to motion sickness even decreased. This point is further elevated through Figure 22. Looking at it, one can see that prior to the test the most severely occurring symptoms on average were fatigue (value: 0,483), fullness of head (value: 0,375), eyestrain and difficulty concentrating (values: 0,250). Taking this as a baseline it can be said that of these “most severe symptoms” all besides eyestrain are exclusive to motion sickness. Comparing that to the results after the test, one will notice that the ranking has changed. The “most severe symptoms” after the test therefore were fullness of head (value 0,563), eyestrain (value: 0,500), headaches, sweating and

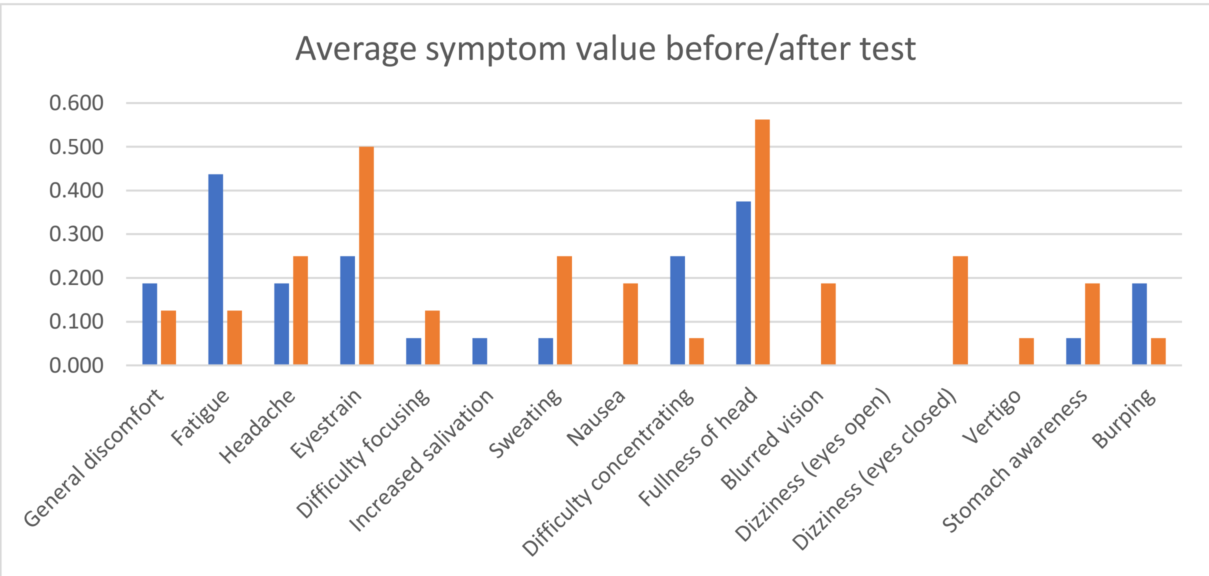

Figure 22: Average value per symptom before and after the test (Source: own representation)

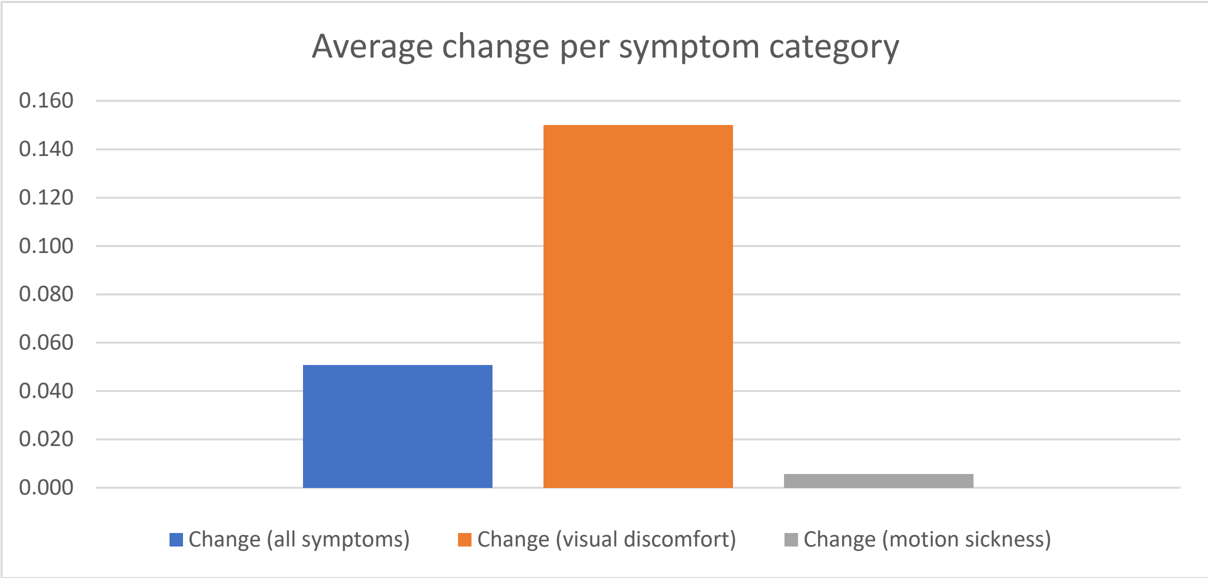

Figure 23: Average change between pre and post exposure answers per symptom category (Source: own representation)

dizziness (eyes closed) (value: 0,250). Thus, the ratio between exclusive motion sickness symptoms and visual discomfort symptoms among the most severe symptoms changed from 3:1 to 2:2. Furthermore, Figure 22 also shows which symptoms saw the largest increase. Comparing the values of pre- and post-exposure reveals that both eyestrain and dizziness (eyes closed) increased by 0,250. The second-largest increase can be seen for the symptoms of nausea, fullness of head and blurred vision which increased by 0,188 closely followed by the increase seen for sweating of 0,187. Therefore, it can be said, that most of the symptoms of visual discomfort (besides and headaches and difficulties when focusing) increased way more than the average of all symptoms. Figure 23 shows these changes between pre- and post-exposure results. While the increase in symptoms exclusive to motion sickness was just

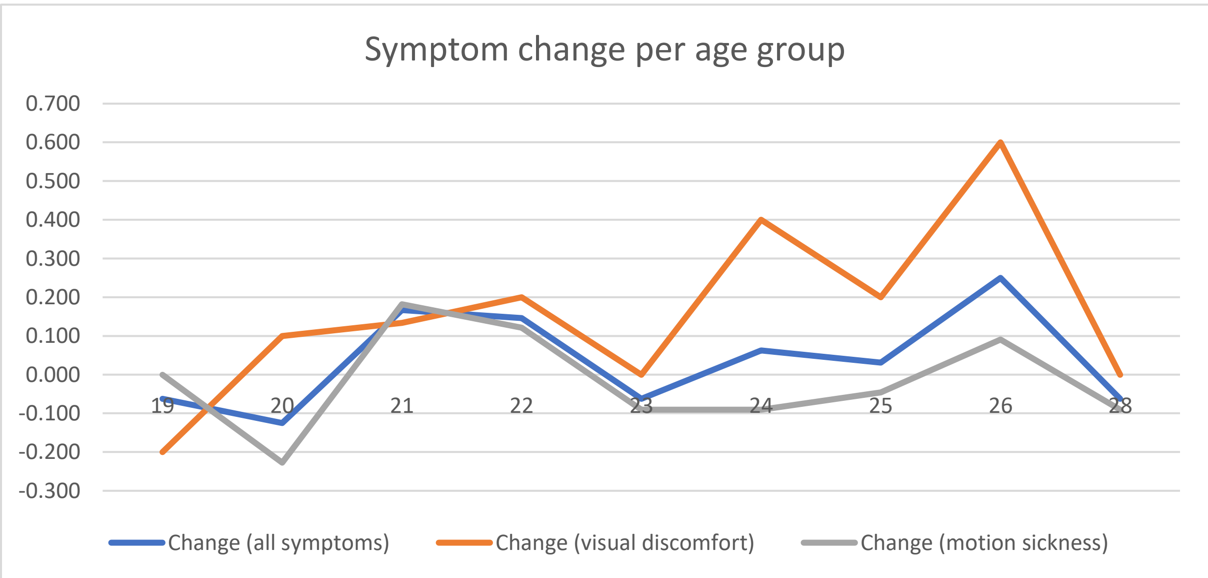

Figure 24: Change between pre- and post-exposure results ranked after age of participants (Source: own representation)

0.006, the increase in visual discomfort symptoms was 0.150, 25 times this value. Even compared to the average of all symptoms (value: 0,051), they still increased almost 3 times as much.

Thanks to the additional information from the pre-test, it was possible to further look for differences between certain parts of the test group. Figure 24 for example, shows the results of firstly sorting the participants based on their age and following that an analysis of the average change of certain symptoms (using the categorization from earlier) per age group. It shows a tendency of visual discomfort symptoms increasing with progressing age. The average of all symptoms as well as those exclusive to motion sickness, however, seemed to remain relatively stable. Furthermore, it should again be noted, that the current test group of 16 participants is much too small to draw firm conclusions. In this case, for example, the age groups often consisted of sometimes only one person (age groups 19, 24, 26 and 28 years) up to a maximum of three people (age groups 21 and 22). Similar limitations apply for the analysis of the results in respect of the previous VR experiences of the participants. Figure 25 shows this result of this analysis. It shows a decrease in severity of all symptom categories when comparing the participants who never used a VR headset before to those that did so once or more. Like before, however, these results are to be viewed with caution as the different groups vary a lot in size. While the first and largest group, for example, consists of 8 people, that of one-time users is only presented by one person.

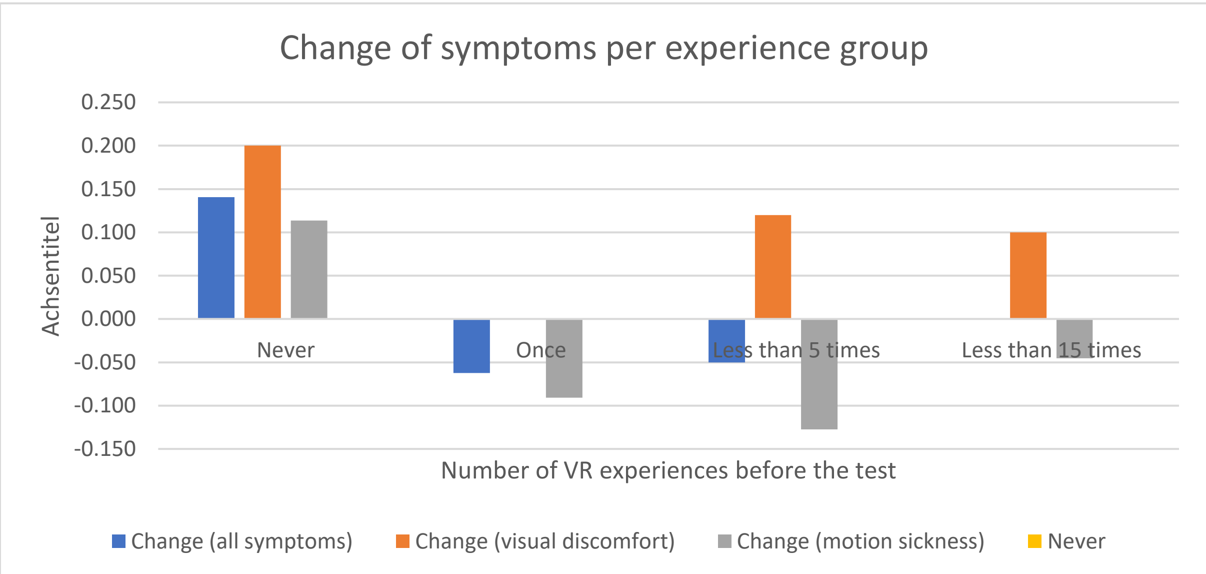

Figure 25: Change of symptoms between pre- and post-exposure ranked after previous VR experiences of the users (Source: own representation)

4.2.3 Individual results

The goal of tracking the amount of time spent at every station per participant was to answer the question if a longer exposure to certain interactions (or in this case stations) would have a visible influence on the visual discomfort of the participants. Therefore, the gathered information was used to compare the results of the participant with the longest exposure to each station with those of the least exposed ones. As shown previously in Figure 19, all stations besides station 4 also included one or several outliers which are, in this case, synonymous with participants that exceeded the "usual" duration time compared to the rest. Sadly, however, this approach did not yield any proper results. While comparing participants this way sometimes indicated a difference, it was not possible to ensure that the differences were caused by the different durations of exposure to these specific stations. Figure 26 displays the change seen for visual discomfort symptoms respectively for the fastest and the slowest participant for each station. However, as mentioned previously, it is not possible to draw firm conclusions from it.

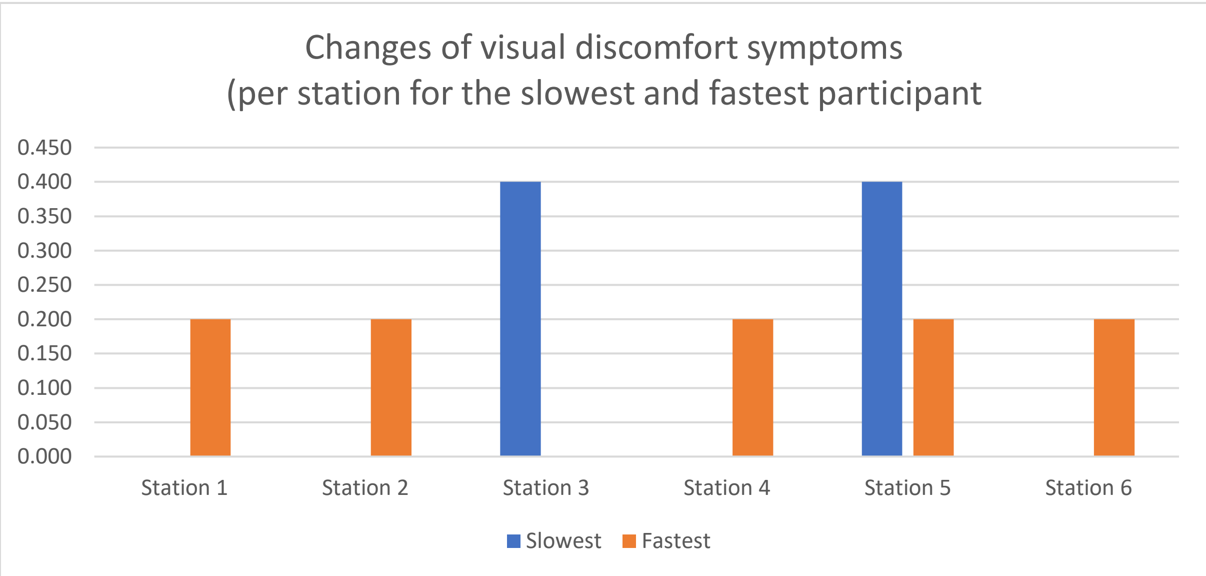

Figure 27: Display of the changes visible for the fastest and slowest participant per station (based on their answers before and after the test) (Source: own representation)

As a result, the author decided to focus on answering the first research question from chapter 3.2 while the second question (whether specific interactions are more influential to visual discomfort than others) must be answered with further experiments.

4.3 Test result summary

After previously reviewing the results gathered throughout all test sessions, this chapter is intended to summarize the results from the test and evaluate whether the tests helped to answer the questions asked in chapter 3.2.

Firstly, it can be said that the test helped successfully to answer the first research question. By designing the test to minimize motion sickness causes while leaving the causes of visual discomfort untouched, it was possible to create a test that showed significant changes for symptoms shared between motion sickness and visual discomfort while showing relatively stable results for symptoms exclusively attributed to motion sickness. Furthermore, the execution of a pre-test successfully ensured the comparability of participants and their results. The SSQ proved to be a proper tool to analyze the severity of symptoms associated to motion sickness. However, as this work aimed to investigate symptoms and causes of visual discomfort, the SSQ had some difficulties. One reason was that the SSQ was intended to investigate simulator/motion sickness. As a result, some of the symptoms attributed to visual discomfort are either not included, like eye dryness for example, or counted among other symptoms, like visual fatigue being counted among general fatigue. Collecting additional information through spoken comments of the participants and measuring the time spent at each station further allowed to identify differences between the interactions.

Summarizing, this design can be seen as a prototype for future instances. Through different means of optimizations, like including more accurate symptom descriptions in the test, therefore adjusting it to those of visual discomfort, or specifying the test for certain interactions, for example only reading, it seems possible to create instances of this blueprint that deliver better results.

5 Conclusion

In this study, the author explored different topics surrounding interactions within the personal space in VR, with a focus on the effect of such interactions on the occurrence and severity of visual discomfort. Therefore, this work aimed two answer two questions. The first question was whether it was possible to design a user test that reveals the influence of these personal space interactions on visual discomfort. The second question, however, addressed the influence of distinguished interactions on the severity of the mentioned visual discomfort.

Bearing these research questions in mind, the author at first explained virtual reality in larger detail, providing a definition as well as insights on its history, and comparing different ways of achieving it. Following that, this study dived deeper into interactions by first defining the term and on that basis, presenting two models. The first of them improves the understanding of interactions within the context of virtual reality systems, whereas the second one is a tool to categorize interactions based on several attributes. Resulting from this, the author used these models to identify interactions within different VR applications. Lastly, the investigation focused on visual discomfort and its main contributing factor – the vergence-accommodation conflict. Exploring this topic, the author initially illustrated the differences between motion sickness and visual discomfort. After explaining the mentioned VA conflict in more detail, the author then created a user test based on the previously gathered knowledge.

The designed test consisted of several different methods that helped to paint a wider picture by providing more information on the participants and their respective experiences throughout the test. Firstly, a pre-test collected more relevant information, like age, gender, and prior VR experiences, as well as ensuring that all participants would be suited for the test, e.g., being able to see stereoscopic images. Following that, the author investigated different VR applications, to find one suitable for the test. As such, it was important that the application would include many interactions within the personal space or consist exclusively of such. By using the previously mentioned model, the author ultimately chose one application and more specifically its tutorial level. The test was then executed with 17 participants. The same test structure was applied for every participant. At first, they filled out the pre-test questionnaire, before continuing with the first instance of the simulator sickness questionnaire. After finishing the subsequent play session, they would complete the second instance of the SSQ and thus finish the test.

The results collected throughout this test were then presented using different types of charts and compared with one another.

5.1 Concluding remarks

In conclusion, this work has shown that it is possible to design a test that reveals the influence of the vergence-accommodation conflict while also distinguishing the symptoms from different causes, like motion sickness. Thus, it also demonstrated that resolving this conflict is an important step towards more comfortable VR experiences in the future. Taking a close look at the VAC, especially its root causes in modern HMDs, also reveals possible approaches to minimizing, or even eliminating this effect. According to the objective of providing guidelines/advice for the implementation of such interactions, a few statements can already be made. In general, these guidelines can be categorized based on the scope at which they are used, namely whether they are implemented on the hardware, software, or interaction level.

Firstly, the hardware level focuses on implementations that aim to improve current limitations. Following that, other studies have shown that there are ways to eliminate the VA conflict, for example using lenses within the headset that adjust the refraction power to the displayed content and therefore eliminate this conflict. These kinds of solutions are likely the most efficient ones as they solve this problem for the whole VR system, in this case HMDs. Yet, such hardware solutions are currently still in development and will likely take a couple more years in development before becoming available to a larger portion of customers, making it necessary to find solutions that are already usable.

This leads to the second layer, namely software solutions. Includes in that layer are solutions, like the implementation of foveated rendering methods. This example of a software solution describes an algorithm, that, based on certain parameters, artificially blurs certain areas of the displayed image to create a more natural viewing scenario in which objects become increasingly unsharp/blurred the further they are away from the object on which our eyes are focused. However, these solutions aim to artificially add cues to the virtual environments that try to mimic those from the real world. As a result, the underlying algorithms must be very precise and therefore need more research of our perception of reality while possibly relying on more information which some VR systems cannot provide yet (for example eye tracking). Furthermore, it should be noted that most of these solutions can only minimize the VA conflict as it continues to exist within the VR system.

Ultimately, this leads us to the third level of interaction-based solutions. This work primarily focused on that layer. While this layer, much like the second layer, can only minimize the VA conflict in most cases, implementing these kinds of solutions is possible with any VR headset as they are mostly focusing on the design of an applications and more precisely the interactions within the personal space it contains. Based on the observations from this study, the following guidelines are suggested:

- **Relevance**: Before implementing interactions within the personal space, the designer of an application should always evaluate which interactions must take place within that space and which must not. As simple as this sounds, almost every interaction in VR can be implemented in different ways. For example, while an application might involve reading documents, this process could also be replaced using audio tracks, therefore making this interaction within the personal space obsolete. As a result, the designer of a VR application should always think of alternative methods and make sure that the final implementation serves its purpose.
- **Duration**: If an interaction must take place within the personal space, the duration of exposure to such interactions should be investigated. While this study could not provide secure evidence on this topic, several other studies suggested that keeping the exposure as short as possible can help to reduce the symptoms of visual discomfort. Furthermore, not just the duration of exposure to one interaction but also to the application in general should be considered. This means that applications which use-cases involve primarily short uses can implement personal space interactions more extensively as the symptoms won't become as severe as in applications that aim for a longer use durations.
- **Balance**: This guideline is linked to the previous one and is based on observations that suggest a balanced use of interactions within and outside the personal space. As closer interactions resemble an extreme scenario for the VA conflict, it can offer some relaxation to our eyes and the underlying visual system if such interactions are counterbalanced with such that are significantly further away. This should be kept in

mind by application designers as they figure out which interactions are taking place and in which order. Therefore, while a long exposure to a personal space interaction might be necessary, this should be met with a long break from such interactions afterward.

Ultimately, studying this issue allows to answer the first research question. The experiment revealed that visual discomfort caused by the vergence-accommodation conflict contributes significantly to the well-being of the user and continues to exist independently of the reduction of motion sickness causes. Yet, it was not possible to answer the second research question and thus could not reveal whether some interactions are more influential than others. Nevertheless, the proposed implementation guidelines can help to deal with the issue at hand until solutions that resolve it entirely are available for everyone.

5.2 Future research

Virtual reality can be considered in an early stage of development. Therefore, many questions remain, which must be answered. As we are trying to develop more realistic virtual environments, understanding our perception of reality becomes ever more important. Since we are often limited to assuming the processes that take place in our brain, tests are essential to prove or neglect our assumptions. While this work has shown a first approach to such tests, specifying them in the future is necessary. As a result, this research could continue in several ways. Firstly, developing a questionnaire that targets visual discomfort more specifically, or at least the differences between it and motion sickness, could provide a good method. Secondly, more tests, that focus on certain interactions, target groups or application scenarios would allow for more results and thus more answers to more detailed research questions. Lastly, it would be very interesting to investigate some of the previously mentioned solutions (mainly hardware and software solutions) and test if they really improve the comfortability of personal space interactions. After all, this study served as a pilot project and therefore served its purpose.

Bibliography

Alsop, T. (3/22/2021): Virtual reality (VR) - statistics & facts. Statista. Online verfügbar unter https://www.statista.com/topics/2532/virtual-reality-vr/#dossierKeyfigures, zuletzt aktualisiert am 3/22/2021, zuletzt geprüft am 27.09.2022.

Alsop, T. (2022): VR headsets - statistics & facts. In: *Statista*, 10.12.2022. Online verfügbar unter https://www.statista.com/topics/10052/vr-headsets/#topicHeader__wrapper, zuletzt geprüft am 15.11.2022.

Burdea, G. (2003): Virtual Reality Technology.-2nd ed. 2. ed. Wiley: Wiley. Online verfügbar unter http://www.loc.gov/catdir/description/wiley039/2002038088.html.

Cambridge English Dictionary: Meanings & Definitions (2023). Online verfügbar unter https://dictionary.cambridge.org/dictionary/english/, zuletzt aktualisiert am 28.01.2023, zuletzt geprüft am 28.01.2023.

Cervantes, E. (2/25/2022): Mobile VR headsets: What are your best options? In: *Android Authority*, 2/25/2022. Online verfügbar unter https://www.androidauthority.com/mobile-vr-803034/, zuletzt geprüft am 15.11.2022.

Chang, E.; Kim, H. T.; Yoo, B. (2020): Virtual Reality Sickness: A Review of Causes and Measurements. In: *International Journal of Human–Computer Interaction* 36 (17), S. 1658–1682. DOI: 10.1080/10447318.2020.1778351.

Choi, J. O.; Forlizzi, J.; Christel, M.; Moeller, R.; Bates, M.; Hammer, J. (2016): Playtesting with a Purpose. In: Anna Cox, Zachary O. Toups, Regan L. Mandryk und Paul Cairns (Hg.): Proceedings of the 2016 Annual Symposium on Computer-Human Interaction in Play. CHI PLAY '16: The annual symposium on Computer-Human Interaction in Play. Austin Texas USA, 16.10.2016 - 19.10.2016. New York, NY, USA: ACM, S. 254–265.

Cruz-Neira, C.; Fernández, M.; Portalés, C. (2018): Virtual Reality and Games. In: *MTI* 2 (1), S. 8. DOI: 10.3390/mti2010008.

Cruz-Neira, C.; Sandin, D. J.; DeFanti, T. A.; Kenyon, R. V.; Hart, J. C. (1992): The CAVE: audio visual experience automatic virtual environment. In: *Commun. ACM* 35 (6), S. 64–72. DOI: 10.1145/129888.129892.

Doane, N. (2015): How to Design a Survey for User Feedback, 16.03.2015. Online verfügbar unter https://www.gamedeveloper.com/business/how-to-design-a-survey-for-user-feedback, zuletzt geprüft am 07.11.2022.

EON Reality (2021): Platform - EON Reality. Online verfügbar unter https://eonreality.com/platform/, zuletzt aktualisiert am 08.09.2021, zuletzt geprüft am 18.01.2023.

Fireproof Studios (2022): The Room VR: A Dark Matter • Fireproof Studios. Online verfügbar unter https://www.fireproofgames.com/games/the-room-vr-a-dark-matter, zuletzt aktualisiert am 14.03.2022, zuletzt geprüft am 18.01.2023.

Hoffman, D. M.; Girshick, A. R.; Akeley, K.; Banks, M. S. (2008): Vergence-accommodation conflicts hinder visual performance and cause visual fatigue. In: *Journal of vision* 8 (3), 33.1-30. DOI: 10.1167/8.3.33.

Hottong, N.; Braun, C.; Neuweiler, F.; Knoop, F. (2019): Accommodation-Vergence Conflict as possible cause of Visual Stress during Personal Space Interaction in Virtual Reality. Hochschule Furtwangen.

HP (2020): 6 Ways Virtual Reality is Changing the World. HP. Online verfügbar unter https://www.hp.com/us-en/shop/tech-takes/6-ways-vr-is-changing-the-world, zuletzt aktualisiert am 01.05.2020, zuletzt geprüft am 27.09.2022.

Sutherland, I. (Hg.) (1965): The Ultimate Display. Online verfügbar unter https://www.semanticscholar.org/paper/The-Ultimate-Display-Sutherland/dce55f83dd425c68e5d1c1714dd0c8bbb43e54d9.

Jerald, J. (2015): The VR Book: Human-Centered Design for Virtual Reality. Perception and Interaction Design for Virtual Reality. First edition. San Rafael: Morgan & Claypool Publishers (ACM Bks, 8).

Jones, J. A.; Suma, E. A.; Krum, D. M.; Bolas, M. (2012): Comparability of narrow and wide field-of-view head-mounted displays for medium-field distance judgments. In: Peter Khooshabeh, Matthias Harders, Rachel McDonnell und Veronica Sundstedt (Hg.): Proceedings of the ACM Symposium on Applied Perception. SAP '12: ACM Symposium on Applied Perception 2012. Los Angeles California, 03 08 2012 04 08 2012. New York: ACM, S. 119.

Junling, W. (2022): Biology/Electronics-Depth perception and 3D movie. howthingswork.org. Online verfügbar unter http://howthingswork.org/biologyelectronics-depth-perception-and-3d-movie/, zuletzt aktualisiert am 17.11.2022, zuletzt geprüft am 17.11.2022.

Kennedy, R. S.; Lane, N. E.; Berbaum, K. S.; Lilienthal, M. G. (1993): Simulator Sickness Questionnaire: An Enhanced Method for Quantifying Simulator Sickness. In: *The International Journal of Aviation Psychology* 3 (3), S. 203–220. DOI: 10.1207/s15327108ijap0303_3.

Kooi, F. L.; Toet, A. (2004): Visual comfort of binocular and 3D displays. In: *Displays* 25 (2-3), S. 99–108. DOI: 10.1016/j.displa.2004.07.004.

Koulieris, G.-A.; Bui, B.; Banks, M. S.; Drettakis, G. (2017): Accommodation and comfort in head-mounted displays. In: *ACM Trans. Graph.* 36 (4), S. 1–11. DOI: 10.1145/3072959.3073622.

Kumparak, G. (3/26/2014): A Brief History Of Oculus. In: *TechCrunch*, 3/26/2014. Online verfügbar unter https://techcrunch.com/2014/03/26/a-brief-history-of-oculus/?guccounter=1&guce_referrer=aHR0cHM6Ly93d3cuZWNvc2lhLm9yZy8&guce_referrer_sig=AQAAAJdH8Jfynci05Sdd1bNf8wSaXuYS9PE8jhXivmAsAg95l31k2XZEzTq_hNa4S3m4X9ot-xTXwRiCjxKxYKw8yKVCKWpddpuJsxypNA45AdiEbEZAM4phOrXkCkxMcefpyezgZ8amKBPXpgJ-ZGYB2jor2O_JN4XU2Opjxfyz_zdD, zuletzt geprüft am 21.10.2022.

Schomaker, L. (1995): A taxonomy of Multimodal Interaction in the Human Information Processing System. Online verfügbar unter https://research.rug.nl/en/publications/a-taxonomy-of-multimodal-interaction-in-the-human-information-pro.

Mackay, W. E. (2013): CHI '13 Extended Abstracts on Human Factors in Computing Systems. New York, NY: ACM (ACM Conferences). Online verfügbar unter http://dl.acm.org/citation.cfm?id=2468356.

Merriam-Webster.com Dictionary (2023). Online verfügbar unter https://www.merriam-webster.com/, zuletzt aktualisiert am 04.02.2023, zuletzt geprüft am 04.02.2023.

Negroponte, N. (1993): Virtual Reality: Oxymoron or Pleonasm? In: *WIRED*, 06.01.1993. Online verfügbar unter https://www.wired.com/1993/06/negroponte-11/, zuletzt geprüft am 21.10.2022.

Oakes, E. H. (2007): Encyclopedia of world scientists. Rev. ed. New York: Facts on File (Facts on File science library).

Oviat, S. L. (2009): Multimodal Interfaces. In: Andrew Sears und Julie A. Jacko (Hg.): Human-computer interaction. Design issues, solutions, and applications. Boca Raton, Fla.: CRC Press (Human factors and ergonomics), S. 286–304.

Perry, L. D. S.; Smith, C. M.; Yang, S. (1997): An investigation of current virtual reality interfaces. In: *XRDS* 3 (3), S. 23–28. DOI: 10.1145/270974.270983.

PwC (2022): What does virtual reality and the metaverse mean for training? Unter Mitarbeit von Scott Likens und Andrea Mower. Online verfügbar unter https://www.pwc.com/us/en/tech-effect/emerging-tech/virtual-reality-study.html, zuletzt aktualisiert am 27.09.2022, zuletzt geprüft am 27.09.2022.

Quinn, M. M.; Symborski, C.; Barton, M.; Korris, J.; Falstad, T.; Granato, S. (2013): Methodology for playtesting serious games A case study using a mixed method approach. In: 2013 IEEE International Games Innovation Conference (IGIC). 2013 IEEE International Games Innovation Conference (IGIC). Vancouver, BC, Canada, 23.09.2013 - 25.09.2013: IEEE, S. 222–227.

Riccio, G. E.; Stoffregen, T. A. (1991): An ecological Theory of Motion Sickness and Postural Instability. In: *Ecological Psychology* 3 (3), S. 195–240. DOI: 10.1207/s15326969eco0303_2.

Shibata, T. (2002): Head mounted display. In: *Displays* 23 (1-2), S. 57–64. DOI: 10.1016/S0141-9382(02)00010-0.

Shibata, T.; Kim, J.; Hoffman, D. M.; Banks, M. S. (2011): The zone of comfort: Predicting visual discomfort with stereo displays. In: *Journal of vision* 11 (8), S. 11. DOI: 10.1167/11.8.11.

Stanney, K. M. (Hg.) (2002): Handbook of virtual environments. Design, implementation, and applications. Mahwah, NJ: Lawrence Erlbaum Associates (Human factors and ergonomics).

Stanney, K. M. (Hg.) (2015): Handbook of virtual environments. Design, implementation, and applications. Unter Mitarbeit von Kelly S. Hale und Kay M. Stanney. Second edition. Boca Raton: CRC Press (Human factors and ergonomics). Online verfügbar unter https://www.taylorfrancis.com/books/9781466511859.

SteamVR - Valve Corporation (2023): Half-Life: Alyx. Online verfügbar unter https://www.half-life.com/en/alyx, zuletzt aktualisiert am 18.01.2023, zuletzt geprüft am 18.01.2023.

Stereoscopes|Encyclopedia.com (2022). Online verfügbar unter https://www.encyclopedia.com/media/encyclopedias-almanacs-transcripts-and-maps/stereoscopes, zuletzt aktualisiert am 08.10.2022, zuletzt geprüft am 11.10.2022.

Treisman, M. (1977): Motion sickness: an evolutionary hypothesis. In: *Science (New York, N.Y.)* 197 (4302), S. 493–495. DOI: 10.1126/science.301659.

Webster, N. (1989): Webster's encyclopedic unabridged dictionary of the English language. 11. [Dr.]. New York: Gramercy Books.

Zone, R. (2007): Stereoscopic cinema & the origins of 3-D film, 1838-1952. Lexington Ky.: The University Press of Kentucky.

Eigenständigkeitserklärung

Ich erkläre hiermit an Eides statt, dass ich die vorliegende Thesis selbständig und ohne unzulässige fremde Hilfe angefertigt habe. Alle verwendeten Quellen und Hilfsmittel sind angegeben. Der Einsatz von KI-Anwendungen ist dem betreffenden Thesisteil, der Art sowie dem Umfang nach detailliert benannt.

________________________________ ____________________________________

Ort, Datum Unterschrift

Contents of the attached USB-Stick

- Complete Thesis document
- Answers to the Pre-Test questionnaire
- Answers to the Simulator-Sickness questionnaire
- Documented station times