Immersion in Virtual reality

Impact Analysis of Virtual Environment and VR sickness

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Abstract

Virtual reality is a technology that allows users to transport themselves into a virtual world using head-mounted displays. It gives user the feeling of actually “being there”, also known as presence. It has found its use in many different fields of application, such as medical, entertainment and education. However, some users can suffer from symptoms of motion sickness, which in the context of virtual reality is called cybersickness or VR sickness. People who suffer from cybersickness are less immersed in a virtual environment. To improve the user experience in VR, it is important to explore factors that can reduce cybersickness and methods to improve immersion and maximize the user experience.

Therefore, this research aims to analyze factors influencing cybersickness reduction and methods to enhance user immersion in VR environments. The central question driving this thesis is: How do various factors contribute to the reduction or induction of virtual reality sickness, and what strategies can be employed to enhance the degree of user immersion in virtual environments?

Through extensive literature research and paper analysis, it is established that the quality of the hardware device, latency, frame rate, optical flow, graphic realism, and human factors such as age or gender play crucial roles in determine the degree of cybersickness. In order to alleviate cybersickness, developers should consider adding additional sensory information and refine the depth of field in a virtual environment.

Factors enhancing the user’s immersion, such as haptic feedback, are examined. In this thesis, an algorithm utilizing the multi scale Retinex and Ostu’s estimation is proposed, which aims to improve the quality of the images and reduce the processing speed, resulting in an improved immersion. Other methods, including audio integration, cues, self-avatars and removing unnecessary information, bring a positive contribution to the overall immersive experience.

List of Abbreviations

3D	Three-dimensional
AR	Augmented reality
CAVE	Cave automatic virtual environment
DoF	Depth of field
FOV	Field of view
GPU	Graphics processing unit
HMD	Head-mounted display
IPD	Interpupillary distance
IVE	Immersive virtual environment
MSR	Multi-scale Retinex
MR	Mixed reality
NPC	Non-player character
SSQ	Simulator Sickness Questionnaire
VE	Virtual environment
VIMS	Visually induced motion sickness
VR	Virtual Reality

Key Terms

Virtual reality
Immersion
Virtual reality sickness

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1 Introduction

Virtual reality (VR) has become more and more present in the last few years. It is widely adapted in different fields of applications, like entertainment, training, education and even healthcare. VR is considered to be a high-presence medium and allows users to transport into a virtual environment (VE) in a way that they develop a sense of presence. [1]

However, besides these advantages there are also some drawbacks of VR. When user consistently receive sensory information that is different from their expectations, they can suffer from symptoms of motion sickness. In the context of VR, motion sickness is also called cybersickness or VR sickness. Users can suffer from eye fatigue, nausea, and disorientation, which can constrain future VR deployment. Cybersickness is regarded as a problem and therefore needs to be solved. [2]

Immersive virtual environments (IVE) completely separate the user from their real surroundings. They increase the degree of immersion immensely and therefore changes the way people experience VR. The user's engagement with a VR system leads to immersion, resulting in the user entering a flow state. VR is getting a lot of attention right now and will play a crucial part in the future. Since the degree of the user's immersion determines the quality of the VR and the user experience, it is essential to understand factors that can reduce or induce the degree of immersion. [1]

It is important to research factors that can minimize cybersickness and enhance immersion due to their impact on user experience and future deployment of VR in various field of applications. In this thesis, I analyze factors that can induce cybersickness and methods to minimize VR sickness symptoms and present methods to increase the degree of immersion in IVEs.

In the first part, this thesis will lay a knowledge base about VR deployment in the medical, healthcare and entertainment field. Afterwards, Cybersickness is discussed, going further into detail about the influence of hardware, content, and human factors on cybersickness. Immediately followed by the factors that can reduce the user's susceptibility to cybersickness. The next part will go further into detail about immersion. Starting with a description about the different types of immersion, followed by a explanation of the different types of immersion. Afterwards, this thesis will propose methods to enhance immersion, with factors such as adding haptic feedback or using the multi scale Retinex (MSR) algorithm and the Ostu's estimation to shorten the processing speed and image quality.

2 Virtual reality

Virtual reality is a rather new technology developed in the 20th century. It generates three-dimensional (3D) visual content in an IVE. The goal of immersive VR is to completely transport the user into the virtual world. This can be achieved with the help of Head-mounted displays (HMD) or multiple projectors. These devices can completely block out the user's real surroundings, immerging them further into the IVE. [3] A HMD is a display device, that is worn on the head. It has a small display optic in front of each eye. It is meant for total immersion, as no matter where the user turns his head, the display is always right in front of the eyes. [4]

Augmented reality (AR) is another type of VR. It connects the real world with the virtual world by enhancing or adding virtual objects into the physical world in real time. The user is not isolated into the virtual world, it rather watches virtual 3D object placed into the real world through a device. One of the most known examples for AR is the game 'Pokémon GO'. Mixed reality (MR) combines the real world with synthetic content. The main goal of MR is that the synthetic content and the real content can react to each other in real time. It is the newest technology and is sometimes referred to as hybrid reality. [5]

2.1 Use of immersive VR

As virtual reality emerges as a new area of multidisciplinary research, it expands its scope into various fields of study [6]. For example, in the field of education, it provides a better opportunity for 3D visualization. Immersive VR is widely used for entertainment purposes, like gaming and sports. VR has also found its use in the medical field, as it allows the students and doctors to interact with the human body and gain experience. [7]
The military industry is always on the lookout for new ideas, therefore it is slowly emerging as one of the major investors into VR. [6]
The next part of this thesis describes the different use of application of VR in various fields.

2.1.1 Healthcare and medical field

The medical industry is adopting VR technology to improve treatment of patients, as it allows doctors to learn new skills in a safe environment. Applications of virtual reality technology in the healthcare industry are psychological therapy, medical rehabilitation, medical research, teaching, diagnosis, planning and performing of surgery, reducing depression, and many more. It helps a surgeon to operate without causing any harm to the real patient and strengthen their confidence in making decision. Doctors who practice in the virtual environment can reduce the error rate in surgery and helps doctors to make less mistakes. Intensive care unit staff can practice a procedure in limited time, during emergency cases. It is extremely useful for building trust and to make informed decisions. It also very helpful in addressing and trying out various neuropsychological issues during the patient's treatment. Besides the learning experience, VR is also immensely helpful for pain management, as it immerges the user into a calming IVE that distracts the user‘s brain and reduces the pain during treatments. In addition, this technology can be used for treating phobias as it allows patients to face their fears and phobias in a controlled virtual environment. The wide range of applications of this technology in the medical field provides an essential role to improve performance of the medical profession. [7]

2.1.2 Digital marketing

As the world is frequently evolving and getting more digitalized, some enterprises need to adjust their methods to promote products and services to customers. To establish and maintain the relationships with clients and other individuals, one of the most important elements is marketing communication. Companies that use modern marketing communication methods and tools can quickly and effectively interact with customers and other entities. One of the latest marketing communication methods is the use of VR. Clients can experience products and service presentations in 3D with a 360-degree rotation option and with very realistic content presentation, so that the user has the impression that they are watching it in real life. In addition, the user can interact, play, and rotate the product to get an overview. VR has also been used to promote businesses and present themselves in industry fairs. These types of promotions are usually more exited for users, since the businesses uses advanced equipment that not everyone has at home. [8] According to [8], VR campaigns have a positive impact on the attitude and general perception of promotional messages towards the products and services that were being promoted, increasing its recognition in the process. [8]

2.1.3 Education and learning

Technology is extremely important for military effectiveness. Therefore, military technologies are also using multiple virtual reality simulations to demonstrate effects of operations in real time. One area where the armed forces take advantage of VR is training. They use it to reduce the risk of being exposed to hazards and to increase confidentiality. In addition, it is employed because "on-the-job training" can be impossible, especially in the context of warfare. As stated in [6], the key to effectiveness of VR in the military field is the man-machine interface or also known as human-computer interaction. They also state that VR devices need to display an IVE that includes the relevant information and responses that is needed to learn and perform military tasks. [6] One of the early employments of VR technology is simulators used for flight training. Many pilots were trained before and during World War II. with flight trainers that were built by the Link Company (Binghamton, New York) in the late 1920’s and 1930’s. To maximize the learning experience, it is essential that every instrument in the simulation is functioning identically to their real-world matching components. Another crucial component to enhance the experience is the immersion of the user. [6]

Another application area that uses VR for learning purposes is the field of education. For example, students can visit museums, far-away cultural sites or travel back in time. It also helps chemistry or biology students to conduct experiments in a safe environment or allow art students to visit art galleries or experience their creations in 3D. As the cost of VR equipment decreases, it also revolutionize both the way students learn and educators teach. Engineering students can design and model their prototypes with no cost, while physic students can experience the effects of gravity on the moon or other planets. VR can also benefit students while learning new languages, as they can immerse themselves into a VE and practice their skills and get more confident without the travel costs. VR in classrooms can be used for students of all ages. For instance, elementary students can improve their retention an deepen engagement. According to [9], students are more motivated when using VR in specific settings.

During the COVID-19 pandemic many schools and universities moved their studies to online courses as it was an essential element for safety to reduce in-person contact between people. Many students could not access laboratories and equipment that was critical for students to develop practical skills. The solution to this problem was the implementation of modern technologies such as artificial intelligent and virtual reality. [10] On the other hand, the cost of implementing VR technology in classrooms is still very high, compared to the costs of textbooks and tablets. The authors in [11] compared traditional teaching methods with VR teaching. They stated that the use of VR in an educational setting can enhance the user's engagement and learning outcome. Users also find the VR teaching more enjoyable. [11]

2.1.4 Entertainment

The definition of the entertainment field is widely broad. It can be divided into many subcategories, including gaming, film industry, galleries & museums, music & nightclubs, arcades & theme parks, tourism, and sport events. [12] The application of VR in the film and television industry is less popular than in other branches. The reason for that is the need to wear HMDs throughout the whole experience, which can get heavy and disruptive after some time. Moreover, the occurrence of virtual reality sickness can be deeply unpleasant for some users. The production of VR films also appears to be extremely difficult, as it requires special production methods and technical means. VR movies require continuous shooting, and the editing process is different in contrast to traditional movies. [13] The use of VR in museums is helping to overcome two major problems: *authenticity* and new *museology*. The former describes the need for museums to present an authentic experience to visitors and the latter outlines the enhancing experience of the visitor by providing edutainment (education and entertainment). [14] In cultural tourism, VR reduces the barrier between travelers and their destination and allows them to enhance their knowledge and provide information about their destination before the actual visit. However, as the authors in [14] mention, VR does not replace or threaten real world traveling, whereas it is an effective tool to prepare for the real vacation rather than a substitution. [14]

Due to the COVID-19 pandemic, nightclubs, bars, and other nightlife venues were forced to close their doors. This led not only to a higher unemployment rate, but it also took away social contact from people. The nightlife scene completely reinvented itself when it shifted from in-person to a virtual performance. [15] VR clubs are gaining more recognition, as it combines the excitement of the traditional nightlife with the new ideas of virtual reality. **Club Qu**, **Bootshaus**, and **VRChat** are examples for VR nightclubs. **Tribe XR** and **Vinyl Reality** offer DJs a platform for virtual training and performance opportunities. For instance, Tribe XR provides a cost-effective and accessible way to learn and perform with digital DJ equipment. Additionally, the users of Tribe XR can stream and listen to the performances of the DJs. [16]

3 Virtual reality sickness

As mentioned above, VR technology has found its use in many branches. However, besides all these advantages, there are also some drawbacks of virtual reality. During VR experiences, some users can experience symptoms that are similar to motion sickness. [2]

Humans get their orientation and self-movement via various sensory organs. To be more precise, they use information from the visual, vestibular (balance system), and proprioceptive (body awareness) senses to form an accurate perception of self-motion within a 3D space. Because the information from the visual, vestibular, and proprioceptive senses is processed synchronously, we can accurately recognize our movement and position without any difficulties. [2]

However, modern transportation systems can disturb the perceptual system. When riding on a vehicle (e.g. plane, car, train), people can feel the movements through their vestibular organs, but sometimes the corresponding visual information is missing, which causes sensory conflicts. When a human consistently receives sensory information that is different from their expectations, the user can experience symptoms of motion sickness. Visually induces motion sickness (VIMS) is the term used, when the dominant sensory input that causes motion sickness is visual stimuli. Depending on the context, VIMS can be referred as something else. In the case of virtual reality, VIMS is referred as simulator sickness, cybersickness, or VR sickness. [2] The terminology simulator sickness originated from the early use of flight simulators in military training [17].

Users that experience virtual reality sickness get symptoms like headaches, vertigo, nausea, disorientation, and eye fatigue. What causes these symptoms are the frequently moving images and the mismatch between expected and perceives sensory information while using a head-mounted device. [18]

There is a balance between how likely a user is to feel VR sickness and their sense of presence in the virtual environment. There is a trade-off between the user's proneness to VR sickness and the sense of presence, which is determined by the velocity and visual angle of the visual content. [18] The degree of presence and cybersickness are inversely related and mediated by factors, such as vection, navigation control, and display factors. The problem is, if more attention is payed to the visual information design to enhance the feeling of presence, the user might develop virtual reality sickness, and vice versa. Therefore, the relationship between the occurrence of cybersickness and the sense of presence is very closely linked and can lead to an unpleasant experience if it is ignored. [18]
In the next part, this thesis concentrates on the focuses on factors that either reduce or enhance VR sickness.

3.1 Factors inducing VR sickness

There are many factors that can influence cybersickness. The authors in [2] categorizes these factors into 3 domains: hardware, content, and human factors.

1. Hardware factors include changes to VR devices, such as display mode, display type, time delay, and many more.
2. Content factors include variations in VR scenes or scenarios by changing graphics or task-related features.
3. Human factors cover differences of individual user that are related with cybersickness.

3.1.1 Hardware

Like mentioned above, there are a few factors that reduce or induce virtual reality sickness. One critical factor is the quality of your hardware. There are devices, like HMD, that deliver stereoscopic images, and other devices, like large screens and monitors, that deliver monoscopic images to user. Although, stereoscopic content can provide high-fidelity and seems more realistic, it also enhances cybersickness. [2]

Hardware & Content FOV
Another factor, that can influence VR sickness is the field of view (FOV), also described as external FOV, display FOV, physical FOV, and real FOV. It is the maximum visual angle of a display device. According to [2], reducing the FOV of a device, decreases the motion sickness, especially during rotational movements or acceleration.
Beside manipulating the hardware FOV, changing the content FOV can also have effects on cybersickness. The study of [19] shows that the symptoms of cybersickness were significantly decreased with a reduction of the content FOV, even though the users did not recognize the reduced content FOV. When narrowing the content FOV, it is important to bring it down to an appropriate level. If the content FOV is reduced too much, the user may not feel as immersed in the IVE. [2]

However, there are several studies, that researched the relationship between hardware and content FOV and their impact on cybersickness. Draper et al. [20] introduced an 'image scale factor' that calculated the ratio between hardware and content FOV. Three categories of images scale factors were assigned based on their values: **minification** (hardware FOV $<$ content FOV), **neutral** (hardware FOV = content FOV), and **magnification** (hardware FOV $>$ content FOV). The results show, that participants find the neutral condition the most comforting. Although a wide field of view generates a great sense of immersion, it also heightens the risk to suffer from cybersickness. In contrast, a smaller field of view allows for a more comfortable experience, but it also decreases the user's immersion. [20]

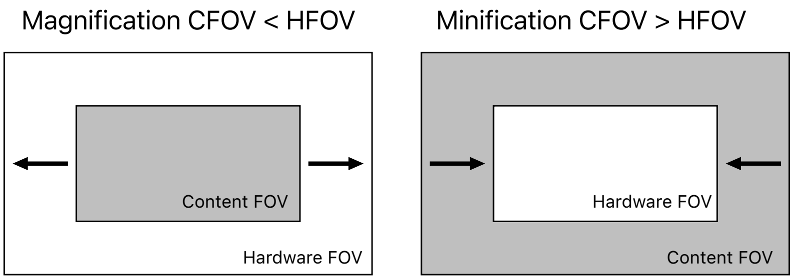

Figure 3.1: Illustration of Magnification and Minification

Latency and Frame Rate
When a user explores and interacts with the IVE, the system needs to calculate the body movement and transmit it back to the user. However, calculating and sending the information back can create a time difference, which causes a divergence between what the user expects to see and what was actually viewed. This sensory mismatch can lead to VR sickness. Studies found, that if the time delay increases, the motion sickness also increases. However, if the time latency is consistent during the whole VR experience, it will not lead to more severe cybersickness [20]. This is because, the user can adapt to the time delay and therefore predict their surrounding precisely. When designing an IVE, that has the goal to keep cybersickness at a low, it is important to minimize time delay or, at least, keep the time lag consistent. [20] Frame rate, however, is a measure of how quickly the frames pass through the rendering pipeline. A lower frame rate can cause flickering, which induces eye fatigue and headaches, whereas a large delay, or latency, can enhance visual sensory conflicts, which contributes to a more intense level of VR sickness. Latency can also arise, when a VE consists of complex graphics, which can lead to a loss in frame rate. [21]

Flicker
Flicker is the brightness fluctuation on displays that can cause VR sickness. It can be visually disturbing and also decrease the user's eye health. Factors, like the display's refresh rate, luminance, frame rate, and FOV can influence flickering. A brighter screen needs a higher refresh rate to minimize the flicker effect. In addition, the size of the screens can also influence flickering. [2] When using a larger display, the user is more likely to experience flicker at the edge of the screen [21]. Nevertheless, due to an improvement in hardware systems in the last few years, flickering was reduced to a minimum and therefore is no longer a major influence in cybersickness. [2]

3.1.2 Content

Content is a critical factor which determines the degree of VR realism and therefore the user's immersion into a VE, as well as VR sickness. Due to the advances in hardware systems, developers could implement a higher fidelity in VR. However, a higher fidelity does not contribute to a better user experience. In order to better understand the influence of context in VR sickness, the authors in [2] categorized six different aspects of VR content, including optical flow, graphic realism, reference frame, content FOV, duration and controllability. In this thesis, the topics of optical flow, graphic realism, reference frame and duration are discussed in more detail. [2]

Optical flow
Humans get more nauseous when they see moving visual content instead of static content. Moving visual content produces the optical flow of the VE and allows a person to experience illusory self-motion. Besides various factors, the moving speed and the number of moving models contribute a lot to the degree of VR sickness. The authors from [22],[23], and [24] report that if the moving speed ascends, the VR sickness also gets more severe. So, Lo et al. [24] investigate the relationship between navigation speed and cybersickness. The root mean square of eight speed conditions (3.3, 4.3, 5.9, 7.9, 9.5, 23.6, 29.6, and 59.2 m/s) are used to manipulate the IVE. The authors in [24] conclude that between 3.3 m/s and 9.5 m/s the severity of nausea increased significantly. Between 5.9 m/s and 59.2 m/s the relationship between navigation speed and cybersickness disappears. The authors in [2], claim that the degree of vection determines the user's discomfort. Vection is an illusion of self-motion, where the user gets visual feedback from the VE, that makes the user think they are moving, without actually physically moving. The speed, that induces a stronger vection, is considered to cause a higher degree of cybersickness. [2] Although the navigation speed does play a crucial part in the degree of cybersickness, if the speed of the VR scene gets too fast and unrealistic, the user might not feel as nauseous because of the vanishing feeling of presence. [2]

Besides the navigation speed, Benato et al. [25] also investigate the difference in the degree of cybersickness during a single-axis or dual-axis rotation. The three rotational motions for the x, y, and z-axis can be referred to as roll, pitch, and jaw. The authors [25] found out that cybersickness gets more severe, when users experience both pitch and jaw movements, compared to only pitch movement. In addition, the authors found out, that there is no difference between a two-axis rotation and a three-axis rotation.

Graphic realism
To increase user's immersion, developers tried to provide more visual content in VR scenes. Besides different strategies, a higher level of visual details and texture can be added. In addition, the level of graphic realism ca be manipulated by adding cognitive cues. Although, a more detailed IVE results in increased immersion, it does not correlate to a better user experience. A higher fidelity of VE content tends to a higher level of discomfort of the user. This results from the sensory difference of visual and vestibular information. For example, some users get a few vestibular information, by sitting in a chair or placing their chin on a chinrest. However, as the fidelity of the VR content and the user's immersion into the VE increases, the desire for more vestibular information rises. If the difference of visual and vestibular information is too substantial, the degree of conflicts as well as VR sickness increases. [2]

Reference frame
The degree of discomfort of a user during a VR experience was significantly reduced, when fixed visual stimuli regardless of the moving VR content was added. For example, clouds or trees were rendered at the same location disregarding of the motion of the VR content. According to [26], when a nose was rendered on a VR scene, the users enjoyed the content for more than one and a half minute longer. The reason for this phenomenon is, that fixed stimuli helps the user to perceive one's position accurately in the IVE. [26]

Duration
The duration that the user needs to explore a VR scene can also have an influence on VR sickness. The longer the exposure time, the greater is the degree of VR sickness. When experiencing VR, it is important to take regular breaks. Besides the occurrence of cybersickness, the heavy weight of HMD devices can cause a discomfort in users. [2]

3.1.3 Human factors

Age
There are a few studies that investigate the relationship between age and the degree of VR sickness. The authors in [27] proposed a study with 10 age groups (9-11, 12-14, 15-17, 18-20, 21-23, 24-26, 27-29, 30-39, 40-49) and evaluated the results using the Simulator Sickness Questionnaire (SSQ). With an increase age, a higher percentage of sickness reports is clearly evident. The age group from 24-26 state the highest sickness report, however they drop slightly between the ages of 27 and 60. [27]

Gender
When analyzing the degree of cybersickness in VR, the gender of the user plays an essential role. The authors in [28] conducted a research with 46 participants, where each participant is assigned to either a controlled group with a flatscreen television (8 females/8 males) or an experimental group with a VR headset (15 females/15 males). Cybersickness was measured by the Simulator Sickness Questionnaire at 0, 15, 30, 45, and 60 minutes post exposure. The results show that there is a significant difference in gender when measuring cybersickness. Immediately after exposure, the adverse effect in females were on average, more than 2x that of males. For females, these effects persisted long after exposure to virtual reality, whereas males recoverd much more quickly. The authors concluded that the interpupillary distance (IPD; distance between the center of their pupils) non-fit is the most significant driver of gender differences in VR sickness. On average, females have an IPD that could not be fit properly to the VR headset, whereas all of the males fit. IPD non-fit leads to misalignment of the VR headset optics and/or inappropriate binocular overlap, which result in perceptual issues. It can also lead to several unpleasant effect, such as increased fusional difficulty, binocular stress, increased near point convergence, fatigue, eye pain, blurred vision, double vision, headache, nausea and many more. A second experiment showed that females that could fit the VR headset properly are not more prone to cybersickness than males. To minimize cybersickness, especially in females, the hardware needs to properly center their pupils to the lenses. Therefore, VR headsets need to be redesigned to have a wider IDP adjustable range. [28]

3.2 Factors reducing VR sickness

3.2.1 Depth of field

In the real world, the human eye can focus on an object, or a part of a scene, while other objects are out-of-focus or blurry. On the other hand, when a user explores a VE with a HMD device, all objects in the scene are on the same screen and in focus, regardless of the user's visual attention. This wave of visual stimuli can have a strong correlation with eye-related symptoms. Depth of field (DoF) was introduced to reduce the enormous amount of visual stimuli. [2] Carnegie and Rhee [29], has conducted a study where the use of DoF should reduce the degree of VR sickness. Users were allowed to explore a VE with a manipulated DoF. Like in the real world, the part where the user wants to focus on in the scene, is very sharp, while the surrounding objects are blurry. Similar to reducing the field of view, depth of field can cut down the amount of visual stimuli that can cause sensory conflicts. In addition, to improve the degree of virtual reality sickness, DoF can also lower the computational cost of rendering the scene, because less objects need to be sharply rendered. [2]

3.2.2 Additional sensory information

When developing a high-fidelity VR, which can enhance the user's immersion, it is very important to implement a VE that includes multisensory information. If the application only contains visual input, the user is more prone to experience VR sickness, due to the sensory conflicts. A VE that contains not only visual content but also audio, olfactory and tactile information is not only more immersive for users but also reduces the sensory conflicts that can lead to cybersickness. With the additional multisensory information, the user can compensate the mismatch between the sensory information. The level of VR sickness was also cut down with the addition of tactile information, like airflow or vibration. However, it is important to produce these tactile stimulations synchronously with the corresponding visual content, or else the immersion will be at disadvantage. [2]

4 Immersion

In the world of VR, the terms immersion and presence are often used interchangeably. However, there is a difference between those two terminologies. Presence is generally defined as a user's subjective sensation of "being there" in a virtual environment. It allows the user to fully immerse into a VE, as if the virtual world is the real environment [30]. Factors like a stable image and accurate tracking can influence the presence of a user. Probably the most important factor is low latency because the virtual world needs to react to a user's movements as quickly as in real-time [31]. Immersion is considered to be a quality of technology, that has the ability to trick your mind into thinking you are somewhere else. Different virtual reality devices can influence the immersion. A virtual system that consists of highly detailed visual content, haptic feedback, and spatialized sound is considered to be more immersive compared to a scene displayed on a desktop monitor. Increased immersion is typically associated with an enhanced sense of presence. [30]
The next section describes the different levels of immersion in greater detail.

4.1 Level of Immersion

The quality and the type of computer generated sensory determines the level of immersion and therefore the users feeling of presence and experience in VR. Ideally, information should be presented to all of the user's senses with high resolution, quality, and consistency across all displays. In order to maintain the illusion of immersion, the VE should react accordingly to the user's action. [32]

VR systems can be categorized into levels based on the degree of immersion they provide to the users. There are three levels of immersion which all differentiate by their physical setup and therefore depend on the degree to which the user is disconnected from the real environment while engaging with the VE. The first level is called a non-immersive system. It has the least amount of physical hardware since it only consists of one computer. Video games and online games are examples for this type of system. The next level of immersion is a mix of the non-immersive system and full-immersive systems. The hardware setup of a semi-immersive VR consists of a display, stereo shutter glasses and some type of input device. Advantages of this system are simplicity, high resolution, low cost, and versatility [33]. The last level of immersion is called a fully immersive VR system. It includes a head-mounted display which provides the user with high-resolution content and a wide field of view. In addition to sight, the user can also experience sound, which makes this type of VR the highest level of immersion. However, according to the authors in [34] a higher level of immersion does not improve the experience of a user, in some cases they even decrease the performance.

4.1.1 Non-Immersive (Desktop VR)

This type of immersion is the least complex to implement in applications, for the reason that it does not need special equipment. It is the simplest type of VR systems, and it is still commonly used today. Desktop VR is when the user experiences the VE using one or more computer screens. One characteristics of a non-immersive VR system is that the user can control and interact with a character, but the environment is not directly interacting with the user and therefore does not immerse the user fully into the game. The only sensory output is the display. The real-time visualization and interaction within a virtual environment, which simulates the real world, are the reasons it became popular in the first place. [32]

4.1.2 Semi-Immersive (Fish-Tank VR)

A semi-immersive system is a combination of non-immersive and fully immersive VR. It provides users with a partially virtual environment where they remain connected to their physical surroundings. It generally does not support sensory output. [32] The user can experience the VE without any physical sensation and still provides them with the feeling of being there. By using a VR headset, the user will not be able to see the real world, only the virtual environment, which will create a strong immersive experience. Semi-immersive VR is the most cost-effective system and therefore the most commonly used form of VR after non-immersive VR. It can be both device-based and web-based. [35] According to the authors in [35], semi-immersive VR is being used by many businesses such as real estate websites, hotels, local bars or pubs, universities, and schools, to promote their location.

Fish tank VR systems, is characterized by a stereo image of a three-dimensional scene, which is viewed on a monitor using a perspective projector coupled to the head position of the user. It is limited by their physical display size that resides at a fixed location. The user sits or stands in front of a display, wearing stereo shutter glasses and holding some type of input device. A tracking device registers the user's head position, so that the images can be presented accordingly. Fish tank VR needs less components than other systems and is therefore easier to set up and cost-effective. However, fish tank VR has a higher resolution than head-mounted device systems and can be used on an ordinary desk. The major drawbacks of fish tank VR are the limited display size and fixed location. In addition, users can only see what is in front of them and need input devices to navigate through the VR environment in order to explore it. [36]

4.1.3 Fully Immersive VR (HMD-VR, CAVE)

With the help of head-mounted devices, users can completely dive into the VE. This last level of immersion is called fully immersive VR, and it has the highest degree of immersion. It is different from other types of VR in that they capture full body motion and can be enhanced by audio, haptic, and sensory interfaces. [32] However, this type of VR is the most expensive one, because you need to buy pricey haptic feedback devices like VR glasses, gloves, vests, controllers or even a body suit with body connectors with sense detectors, that allows user to touch and feel objects within the IVE. These devices are crucial for providing a tactile sense of immersion since they add a sensory dimension to the experience. [37]

In addition, fully immersive VR needs advanced technology that can detect and handle the movement of the users with powerful graphics processing units (GPUs) that all together create a seamless and responsive virtual environment [35]. The core hardware of a fully immersive VR is the HMD. Users wear this device on their head. It contains two displays for each eye, which create a stereoscopic 3D effect. Oftentimes, these HMD have integrated sensors that can track head movements, which allows the users to look around in the VE. Since this form of VR is the most immersive one, it has found applications in industries like training and simulations, architecture and design, gaming and education. It enhances the user's ability to learn, create, and explore. [37]

Another example for a fully immersive VR is a Cave automatic virtual environment (CAVE). A CAVE system is a VE that consists of a cube-shaped VR room or a room-scale area, where the walls, floors and ceilings are projective screens. Depending on the technology, the user can wear a VR headset or a head-up display. The user can interaction with the VE through input devices such as a joystick, wands, or data gloves. Room-sized computer graphics, stereoscopic displays and motion-tracking sensors create an IVE for one or more users. The HMD is synchronized with the projectors that display the graphics on the screens. Sensors all over the CAVE track the users movement and position and align the perspective accordingly. In addition, a haptic system, that provides user with touch and tactile sensation can make the IVE even more immersive. [38]

4.2 Different types of Immersion

When talking about immersion we have to differentiate a few types of immersion. The first type is **tactical immersion**. This type of immersion is experienced when performing tactical operations that require skills. Users are highly concentrated and focused while completing a task that results in success. [32]
Specially in the VE, tactical immersion occurs when a user is intensely dedicated in the act of competing and playing a virtual game, which often requires a fast reaction time. There are not many factors that can influence the tactical immersion. It is mostly determined by the limited amount of time for the user to consider the whole gaming situation thoroughly and the spontaneous response and decision making of the user. Another word for tactical immersion is cognitive immersion or strategic immersion. [39]

Spatial immersion is the type of immersion that transports the user into a IVE, giving the feeling of "being there" in a virtual world, that feels like a real world [32]. It is triggered and maintained by the spatial qualities of the VE. Spatial Immersion can occur, with the help of manipulating a few spatial compositions, such as swift zoom-in and zoom-out, abrupt changes of the camera angles and so on. These filmic experiences create a feeling as if the user can actually feel and touch anything in the VE. Although for some users, these created illusory experiences can evoke symptoms of cybersickness, for others, these kinds of stimulations can increase adrenaline and therefore the excitement and presence in storytelling. [40]

Another important immersion type is **emotional immersion**. Another word used for emotional immersion, is narrative immersion [40]. Users get so invested in a game story that they feel like they are actually part of the game. It is a similar experience to reading a book or watching a movie [32]. The difference to spatial immersion is, the user does not feel the "bodily presence" into the scene, but rather feels the connection and emotionally empathized with the story of a character or an avatar. A user can feel all sort of emotions when playing a game, like fear, joy, excitement, relief, anger & frustration, surprise, boredom, and so on. [39]

Psychological immersion allows a user to get psychological satisfaction in the interaction with virtual characters, so that the user can completely immerse himself in the VE. The psychological immersion lets the users forget about time and their real environment, almost forming a state of selflessness. Physical and psychological immersion is closely intertwined. When physical immersion reaches a certain position, psychological immersion will take over. Even if the VE is not very interactive itself, users can still reach psychological immersion if the content presented is interesting enough to catch their attention. [41]

4.3 Improving Immersion

4.3.1 Haptic feedback

Haptic feedback is the use of physical stimuli, like vibration, pressure, or a button-clicking sensation, to stimulate tactile experience, that the user can feel on their skin or body through a body suit or gloves. It provides the user with the sense of touch with both tactile (cutaneous) and kinaesthetic (proprioception) feedback. Tactile feedback allows the user to feel sensations such as temperature, texture, and vibration. On the other hand, kinaesthetic force feedback lets the user feel a force that is applied to the body with the help of sensoric cells. This allows the user to feel and measure the weight of objects in virtual environments. [42]

Keyboards, computer mice, and wands are all input devices that are unable to provide a natural sense of touch and sensation. Since we react based on our surroundings and how we perceive things, it is very important to understand the nature of touch interaction. Researchers at Texas University proved, by adding sensory cues, the users were able to detect hidden objects. The study consisted of 3D object, that were made invisible. By separating the visual and haptic components, the user had to rely on the feeling of touch to find the hidden objects. Implementing tactile and force feedback to your IVE, can rapidly enhance the fidelity of the VR. [42]

A haptic rendering algorithm is needed when implementing haptic feedback. It consists of two steps:

1. It is crucial to implement a collision detection that recognizes if the user's pointer is colliding with an object. The strength of the penetrations and the exact location of the impact is determined in this step.
2. The next thing that needs to be implemented is collision response. It computes the interaction force when a collision is detected. The return values are force and torque vectors that are then sent to the haptic interfaces of the user.

When implementing haptic feedback to your IVE, users have a new way to manipulate and interact with objects in the virtual world. [42]

4.3.2 Improve Image processing

Like I mentioned in chapter 4, latency plays a crucial part in the degree of cybersickness. The authors in [43] proposed an algorithm that improves the sharpness of the image in order to enhance the quality of the images, and minimizes the processing speed, to mitigate immersion problems during the VR experience. They utilize the multi scale Retinex (MSR) algorithm to improve the quality of the images and the approximate threshold estimation in Ostu's to heighten the processing speed. The proposed protocol eliminates the unnecessary information hiding in the images to enhance the sharpness. To improve the quality, the input image is compressed and subjected to the MSR. MSR detaches the original image from the unwanted components using the Gaussian Filter.

$$\iint G(u,v)\mathrm{dudv} = I_I \tag{4.1}$$

In the equation 4.1, I_I is the input image and G is the Gaussian filter. The results obtained from the application of the equation are normalized to a range of values between 0 and 255. Additionally, the Gaussian Filter, and the weighted average of the neighboring function are used to enhance the image quality.

$$MSR(u,v) = \sum_{n=1}^{N} w_n log I_I(u,v) - log[G_n(u,v) * I_n(u,v)] \tag{4.2}$$

Using the equation above, the data that are light source are extricated by acquiring a 3D image. Improving sharpness is done using the weights function by applying the weights. This will balance out the shininess in the dark and the bright areas of the image. This method estimates the boundaries of each image and identifies the segmented boundaries. The determined weights are then applied to each border. The Ostu's segmentation estimates the weights. The processing speed is determined by analyzing the elements within the images observed in the output in a specific duration. Unnecessary image components are deleted to improve the speed of the processing images.
The Ostu protocol has a very high processing speed in computing the images. The next two equations show the process of the Ostu protocol in determining the weights.

$$class\hat{}2_{\text{weight}}(t) = \text{weight 1 }(2) Class\hat{}2_1(t) + \text{weight 2 }(t) Class\hat{}2_2(t) \tag{4.3}$$

$$\text{Weight 1 }(t).\text{weight 2 }(t)[\mu 1(t) - \mu 2(t)]^2 \tag{4.4}$$

As we can see above, the weight 1 and weight 2 are both the probability across the two segregated classes class 1 and class 2. The maximization of inter-class variance is equivalent to the minimization of intra-class variance. The authors in [43] tested out the laid out method to enhance the quality of the images and the speed of the processing images and came to the conclusion that it actually improves quality and speed. [43]

5 Design of Virtual Environment

Virtual reality is a convenient tool to simulate real-life events and study human behavior as it allows researchers to fully immerse participants into a controlled virtual environment. VR is considered to be a high-presence medium and allows for a high degree of experimental control. Therefore, VR has been used for diagnosis, clinical education, and clinical and experimental intervention. [30]

VR has the potential to study human behavior without exposing the participants to the risk and inconsistencies that can occur in the real-world environment. Another advantage of studying human behavior in IVEs is the full control of the social interactions and other environmental factors, such as noise and crowding, that can take place in the real-world environment and change the way a human would react naturally. [30]

An IVE, that was designed with highly visual content, spatialized sounds, and haptic feedback is considered to be more immersive than a scene that was rendered on a computer. Thus, portable HMDs that have the ability to block out the real-world surroundings are preferred while studying human behavior. Beside the advantages of HMDs, there are also some disadvantages that need to be considered when designing an IVE. As participants do not see their real body, developers need to consider the fact to include avatars. Participants also need the ability to navigate through the virtual space. When designing an IVE, it is important for developers to acknowledge a few elements, that play a big role in the immersion of the user. Factors such as, avatars, audio, light, and other context play a crucial part and need to be carefully studied. [30]

This next section explores key factors that are crucial for enhancing immersion in virtual environments. By focusing on elements such as the degree of detail, virtual environment content, cues and avatars and non-visual sensory information. Developers can optimize the immersive experience, providing a more fascinating and engaging virtual world for users.

5.1 Degree of detail in the environment

Researchers proposed that typical element features, such as furniture, need to be included in an IVE. However, they should have an appropriate amount of detail according to the kind of behavior that researchers want to study. For example, when studying gambling behavior, elements like paper slips, pens and stools in the betting shop need to be considered and included. Realistic textures are very important in studies where participants are expected to move around the environment and pick up items to investigate them. [30]

Providing elements with a realistic texture can improve the participant's sense of immersion. Visual realism has two components: the **geometric realism** and the **illumination realism**. The former investigates the similarity between virtual and real objects and the latter concentrates on the fidelity of the lighting model. However, designing complex IVEs can be very time-consuming, in need of heavy computational algorithms and can decrease frame rate when users view the IVE. Before committing to a final design, researchers need to decide the level of complexity of their IVE, as a suboptimal design can have a serious impact on the user's behavior. It also needs to be considered when using a high level of visual realism, it might rise the participants expectation for other aspects (e.g., non-visual, and tactile) of the virtual environment. Researchers also need to consider what elements are relevant and irrelevant, hence users could pay more attention to irrelevant elements. [30]

5.2 Virtual environment content

Relevant and irrelevant elements
Prior to developing IVEs for behavior analysis, researchers must determine the essential contextual cues and determine VRs capability to integrate all the necessary elements. The inclusion of social elements, which are elaborated on in the next section, present particularly complex trade-offs. Participants often put their focus on objects most relevant to looking behaviors, such as windows. They also engage in more exploratory behavior, which are not very prominent in the real environment. Exploratory behavior in this context can be explained as paying more attention to objects that are not relevant to the research question. [30]
Participants put their focus on more irrelevant parts of the IVE, like "see-through" objects (e.g., windows) instead of practical objects with functionality. The intense attention to display surfaces or windows underlines the concept of multiple incorporation of elements during interaction in virtual environment. The spatial awareness of participants in an IVE is however still embedded in their real surroundings. For example, if participants are more observant of windows or display surfaces that display information's about the exterior, participants may be creating a mental model of the IVEs location and themselves in the virtual space. Therefore, researchers and developers should deliberate on whether certain features, like windows or displays, should be incorporated, or left out, given the fact that participants could pay more attention on irrelevant features. [30]

Stimulatory and instructional cues
Cues, like stimulatory and instructional cues, can be very helpful to participants, considering they provide relevant information and navigation within the IVE. For example, using lighting and moving traffic allows the participant to develop a sense of time. However, such cues should be used carefully as it should only emphasize an emotion of the participant and not affect the playability and navigation in the IVE. Instructional cues can assist participants in navigating through the virtual environment. [30]

Animating interactions
If IVEs contain features that are animated (e.g., walking avatars, moving cars), it is important to consider the right animation speed. When selecting the animation speed for a character or avatar, it is crucial to consider the age and gender of the character. To maintain the feeling of immersion, there should be minimal to no movement mismatches. These mismatches can happen when participants rotate or move their body. [30]

5.3 Social cues and Avatars

When introducing self-avatars in an IVE, there is a possibility that it can enhance a participant's immersion. Users feel more immersed when there is a representation of themselves in the IVE and other avatars recognize them. It also helps them with cybersickness, because the users can perceive one's position accurately in the IVE. [30]

When avatars or self-avatars are introduced, it is essential to animate them appropriately. Social cues are features that a participant can interact with, like avatars. In certain cases, avatars can enhance the realism of the IVE. However, they can also distract the participants and distract their focus to something not important. [30]

5.4 Non-visual sensory information

Audio
There are not only visual aspects of VR that can have an impact on the immersion. Non-visual aspects such as audio or haptic feedback can also change the way a user feels immersed in a VE [44]. Developers should determine if sound enhances the realism of an IVE or might confound the study. Rain, storm, wind, cars driving by, people talking, birds chirping, and other sounds can make a virtual experience more realistic. To maintain the immersion, certain sounds, such as the voice of avatars or non-player character (NPCs) should be gender specific. [30]

Light and shadows
Not only the design aspect of the assets has an impact on the immersion of a user. The realism of the assets is also very crucial. If a model is placed under light, the user expects the model to throw a shadow. Not only does the user expects there to be shadows, but also awaits the objects to look darker in the shade than in the sun. If there is water or some other fluid inside the VE, the player also wants to see some refraction of the light. [44]

6 Conclusion

In conclusion, the aim of this thesis was to examine various factors that contribute to either the reduction or induction of cybersickness, and what strategies can be used to improve user's immersion in IVEs. Investigating into factors influencing cybersickness, including hardware, content, and human factors, has provided valuable insight for moderating these challenges. In addition, this thesis proposed several methods to maximize the user's immersion and therefore provides a better user experience.

The results show that latency and frame rate can have a big impact on cybersickness. If the latency gets too high and the mismatches between the visual input and the expected input is to significant, the user is more likely to suffer from cybersickness. However, if the latency is continuous throughout the whole VR experience, the user can get accustomed to it and will experience less cybersickness. Research shows that a higher frame rate leads to an improved degree of VR sickness. The thesis looked into the moving speed of moving objects and its impact on cybersickness. The results show that if the speed of moving objects is between 3.3 m/s and 9.5 m/s, the VR experience is considered more endurable.

Narrowing down either the hardware FOV or content FOV reduces the visual input. If the hardware FOV and content FOV are exactly the same (neutral), it is perceived as more comfortable. Research shows that if the graphic realism is enhanced, the user expects more vestibular information. However, if the difference between visual and vestibular information is too substantial, cybersickness will arise. In addition, users that are between the age of 24 and 26 state a higher sickness report than any other age group. However, female VR users are more prone to cybersickness, due to their IPD. IPD non-fit cannot align their pupils straight with the hardware device. Therefore, VR headsets need to be redesigned to have a wider IDP adjustable range.

In addition to examining factors that may trigger cybersickness, this thesis explored strategies for mitigating its effects. Adding a depth of field to your IVE can make it more realistic. By only sharply rendering the part of an IVE where the user is focused on, it not only reduces cybersickness but also reduces computational cost since the other parts can be blurred out. Besides visual content, developers should consider adding additional sensory information, such as audio, olfactory, and tactile information. Additional information reduces the sensory mismatches. However, they need to be synchronously with the visual content.

Besides factors that influence cybersickness, this thesis examines methods to improve user's immersion in an IVE. Introducing haptic feedback allows the user to feel sensations, such as texture, temperature, and vibration. It helps the user to perceive themselves in the virtual world. An algorithm that can improve the image quality and reduce the processing speed is introduced. By using the multi scale Retinex and Ostu's estimation, the unnecessary image components are deleted, to sharpen the image and speed up the processing speed.

Lastly, this thesis proposed ways to manipulate an IVE in order to enhance immersion. Designing an IVE with a high degree of realism might raise the expectations for other aspects,

such as non-visual and tactile. It also needs to be considered what elements are relevant and what are irrelevant, since users pay more attention to unnecessary components. Like windows, that could distract them. Adding cues, that contain helpful information, helps the user to navigate through the IVE. Lightning and moving objects allow the user to develop sense of time.
In order to enhance the feeling of immersion, the addition of audio, light, self-avatars, and shadow play a critical role. With this additional information the border between virtual world and real world becomes blurred.

In conclusion, this thesis contributes valuable insights to reduce or enhance cybersickness in virtual reality, offering approaches to intensify user experience and mitigate discomfort in immersive environments. Finding the right balance is the key to a successful VR application.

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Appendix