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Master Thesis

Methods for implementing user movement in VR

Bartłomiej Stanasiuk

keywords:
Virtual Reality
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Head Collisions

short summary:
This study examined the following four different solutions to the problem of VR head collisions: screen fade, delayed push-back, instant push-back, and teleportation. The results of performed experiments showed that some solutions to the problem of VR head collisions have more positive effect than others on VR sickness, the sense of presence, and the usability level.

Supervisor	Dr inż. Marek Kopel	5.0 (bdb)	
	Title/ degree/ name and surname	grade	signature
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Przewodniczący Komisji egzaminu dyplomowego	dr hab. inż. Dariusz Król	5.0 (bdb)	
	Title/ degree/ name and surname	grade	signature

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Abstract

Head tracking systems play a big part in virtual reality (VR) movement. They are used to estimate the position and rotation of VR headset. Unfortunately, they also introduce a significant problem with head collisions that is not normally present in traditional video games. The problem occurs when the user's head should collide with some virtual object, but the user keeps moving his head forward in the real world without any obstructions. In the result, the user sees the insides of the virtual object and unexpected clipping artifacts, which can break the gameplay and immersion of the game.

The objective of this study was to examine different solutions to the described problem and to determine what effects they have on VR sickness, the sense of presence, and the usability level. The following four methods were chosen and implemented: screen fade, delayed push-back, instant push-back, and teleportation. 20 participants were recruited and completed the experiment, in which they had to collide with 10 various objects while using one of the methods. After testing each method, they filled in post-test questionnaires that measured what effects these solutions have on many different factors.

The questionnaires results were analyzed using statistical tests and interpreted to determine which solution should be used in future VR applications. The results confirmed that some solutions to the problem of VR head collisions have more positive effect than others on VR sickness, the sense of presence, and the usability level. Overall, the screen fade method turned out to be the most efficient one of the four solutions and should be the first choice for VR developers. The instant push-back method had mostly neutral results and can be used if the developer does not want to obstruct the vision of the users at any time. The teleportation method achieved substandard scores and generally should not be preferred. The delayed push-back method ranked the worst in all categories and should be avoided by VR developers.

Streszczenie

Systemy śledzenia ruchu głowy odgrywają dużą rolę w poruszaniu się w wirtualnej rzeczywistości (VR). Używane są do śledzenia pozycji i rotacji hełmów VR. Niestety wprowadzają także znaczący problem z kolizjami głowy, który nie jest normalnie obecny w tradycyjnych grach video. Problem pojawia się, gdy głowa użytkownika powinna kolidować z wirtualnym obiektem, ale użytkownik może nadal poruszać głową w prawdziwym świecie bez żadnych przeszkód. W rezultacie, użytkownik widzi wnętrze wirtualnego obiektu i nieprzewidywalne graficzne artefakty, które mogą popsuć rozgrywkę.

Celem pracy było zbadanie rożnych metod rozwiązujących opisany problem i ustalenie jaki wpływ mają one na chorobę wirtualnej rzeczywistości, uczucie obecności w wirtualnym świecie, oraz poziom użyteczności. Wybrano i zaimplementowano cztery następujące rozwiązania: zaciemnienie ekranu, opóźnione odepchnięcie, natychmiastowe odpychanie, oraz teleportacja. 20 ochotników ukończyło eksperyment, w którym trzeba było kolidować z 10 różnymi obiektami jednocześnie używając jednej z metod. Po przetestowaniu każdej metody, uczestnicy eksperymentu wypełniali kwestionariusze, które służyły do zmierzenia wpływu metod na różne czynniki.

Wyniki kwestionariuszy zostały przeanalizowane przy użyciu metod statystycznych i na ich podstawie zostały wyciągnięte wnioski. Wyniki potwierdziły hipotezę, że niektóre rozwiązania problemu mają bardziej pozytywny wpływ na badane czynniki. Metoda zaciemnienia ekranu okazała się być najbardziej efektywna i powinna być pierwszym wyborem producentów gier VR. Metoda natychmiastowego odpychania osiągnęła neutralne wyniki i może być użyta zamiast metody zaciemnienia ekranu, jeżeli producent gry nie chcę kiedykolwiek zasłaniać użytkownikom widoku ekranu. Metoda teleportacji osiągnęła niezadowalające wyniki i nie powinna być preferowanym wyborem. Metoda opóźnionego odepchnięcia osiągnęła najgorsze wyniki ze wszystkich rozwiązań i powinna być unikana.

Contents

Chapter 1

Introduction

1.1 Background

Virtual reality (VR) has become increasingly popular over the past few years. Several tech companies, such as Google, Facebook, Sony, Samsung, or HTC, released many affordable consumer-grade VR systems. Room-scale and seated VR experiences are now easily accessible to anyone interested in this trending technology. Besides entertainment purposes, today's VR has found applications in education, training, healthcare, architecture, and many other areas. However, while VR technology has seen rapid development and growth in recent years, it still has much to improve upon. Modern VR systems lack the ability to simulate realistic haptic sensations and the sense of smell. They also do not have eye tracking capability, which would provide a whole new way to interact with VR content. The current challenge is to increase the sense of presence in virtual environments using the available technology. Another concern is virtual reality sickness that can occur during long exposures to virtual environments. This sickness is mostly characterized by disorientation disturbances and its symptoms resemble the ones seen in motion sickness.

There has been a lot of study into reducing the effects of virtual reality sickness. Because one of the main reasons for the sickness is a mismatch between the virtual and real motions, most of the research has been focused on various locomotion techniques. These techniques have been thoroughly studied in terms of VR sickness, sense of presence, usability, and user experience. A selected handful of these techniques have been chosen as the most comfortable for the users and are now implemented in almost all VR applications. However, there is still much room for improvement, and there are still many issues to solve. This study focuses on one particular problem related to head tracking systems.

The head tracking systems play a big part in VR movement. They are used to estimate the position and rotation of VR headset. The users can now control the virtual camera with their physical head movements. There is no longer a need for a mouse or another input device to look around in the virtual world. Head tracking greatly increases the immersion experienced by the users and can be successfully applied to many locomotion techniques. Unfortunately, it also introduces a significant problem with head collisions that is not normally present in video games. The problem occurs when the user's head should collide with some virtual object, but the user keeps moving his head forward in the real world without any obstructions. The physical collision with the object is currently impossible to simulate due to the lack of advanced haptic systems. Instead, the user sees the insides of the virtual object and unexpected clipping artifacts, which can break the gameplay and immersion of the game. There is a need for solution to the problem that would prevent this situation from happening in future VR applications.

1.2 Research Objectives

Because head tracking is a relatively new technology and most recent studies on VR movement were focused on comparisons of various locomotion techniques, there is a general lack of research into the described problem of VR head collisions. In recent years, VR developers were forced to develop their own solution to the problem if they wanted to prevent the players from clipping through walls and other objects. This led to the creation of many techniques, each with their advantages and disadvantages, and each with their supporters and critics. The main goal of this study is to examine the most promising solutions and to decide which one of them is best suited for future VR games. However, the quality of VR experience can be measured by many factors and some developers may consider different aspects to be more important than others. Most researchers that study VR movement take into consideration VR sickness, usability of examined methods, and the sense of presence in virtual environments. These factors are often measured in experiments using popular and proven questionnaires.

To summarize, the objective of this study is to examine different solutions to the VR head collisions problem and to determine what effects they have on VR sickness, the sense of presence, and the usability level. The results received from questionnaires measuring these three factors should help developers decide which one of the examined solutions they want use in their VR applications.

1.3 Scope of the Study

Due to time constraints, only four most commonly used solutions to the problem of VR head collisions are examined in this study: screen fade, delayed push-back, instant push-back, and teleportation. In the screen fade method, the whole screen fades to black when the head collision is detected. In the delayed push-back method, the user can look inside some object for a brief moment until he is slowly pushed backwards if the collision is maintained. In the instant push-back method, instead of the slow push-back, the user is instantly moved backwards by a collision vector. In the teleportation method, once again the user can look inside the object for a brief moment before he is teleported to a nearby collision-free location. These techniques are described in details in the literature review and methodology chapters. There are no official names for these solutions and the ones used in this study were chosen based on their description. Therefore, in future research studies these specific techniques can occur under different names.

The next chapter is a literature review. It presents an in depth investigation of the literature relevant to the methods for implementing user movement in VR. It outlines the current state of art of virtual reality technologies and examines various locomotion techniques with different input methods. It also describes in details the problem of VR sickness and the problem of VR head collisions, which is the main focus of this study. The methodology chapter presents the research questions that this study seeks to answer and defines the hypotheses that it tries to prove. It also contains the description of questionnaires, implementation, design, participants, and equipment used in the prepared experiment. The methodology section is followed by the results obtained from the experiment, which were analyzed using various statistical methods, and the discussion chapter that interprets the data. Finally, the conclusions chapter summarizes the major findings of this study, highlights the limitations, and ends with recommendations for future research.

Chapter 2

Literature Review

2.1 Virtual Reality

With the launch and success of modern technologies like Oculus Rift, HTC Vive, or Playstation VR, today's virtual reality is mostly associated with a head-mounted device that provides this experience for the wearer. Virtual reality headsets combine a stereoscopic head-mounted display (HMD), stereophonic sound, and sensors like gyroscopes or accelerometers for head motion tracking. The main goal of these devices is to fool user's senses, make him feel present and immersed in virtual reality. A person using such equipment is able to move and look around artificial world. The illusion of 3D depth is achieved by presenting two offset images separately to the left and right eye of the user (see Figure 2.1). Usually users can also interact with the virtual world's features by using specially designed controllers. Today, VR headsets are mostly used for gaming, simulations, education, movies, and other entertainment purposes.

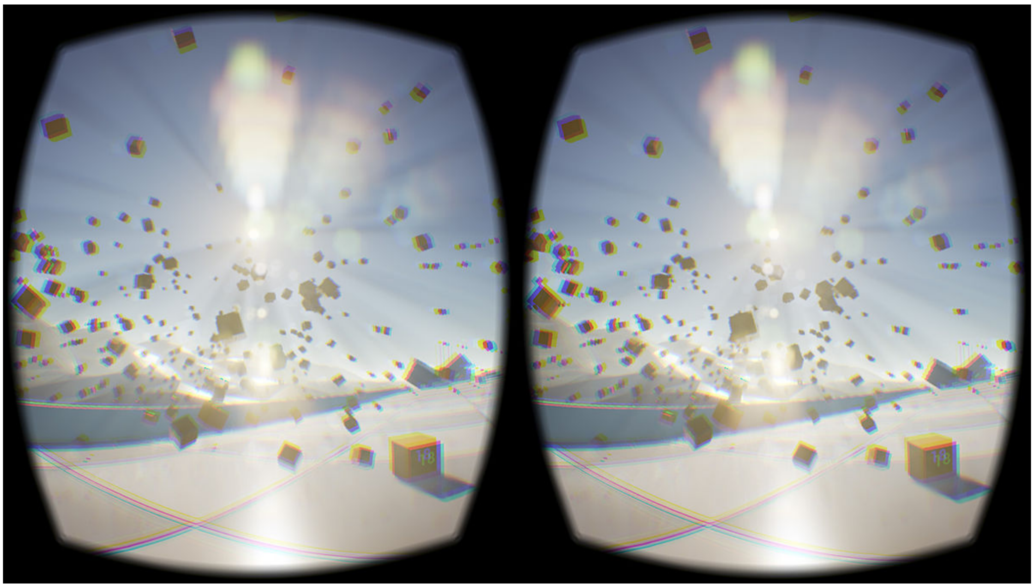

Figure 2.1: An example of the stereoscopic image that is displayed in VR headset (image source: [24]).

The concept of virtual reality is evolving and changing quickly. The technologies we use now will probably become obsolete in the next five years. To describe what virtual Reality really means, the definition must be broad enough to enclose what it meant in the past, what it is today, and what it can become in the future. S. M. LaValle in his book [26] tries this approach to define VR in general way. The four key concepts that appear in his VR description are:

- *Targeted behavior*: The experience from the real world we try to replicate. It could be anything from walking, dancing, swimming, shooting arrows, etc.
- *Organism*: Any life form can be the user of VR. In the past it was tested even on animals like cockroaches, fishes, monkeys and rodents.
- *Artificial sensory stimulation*: With the use of available equipment and technology, organism's senses are tricked to make him feel present in artificial reality.
- *Awareness*: While being immersed in VR, the user should be oblivious to any interference. Feeling presence in this altered or another world is accepted as natural.

Virtual reality has a long history that can be traced back even to 1962, when Morton Heilig built a machine called Sensorama. The machine could provide body tilting, supply stereo sound, display stereoscopic 3-D images, and trigger tracks of aromas and wind during the film [16]. Later in 1968, Ivan Sutherland invented what is regarded as the first head-mounted display device: The Sword of Damocles. The system provided basic user interface and realism. The graphics of created VR were simple wire-frame model rooms [40]. The device was so heavy that it had to be attached to the ceiling with a mechanical arm (see Figure 2.2). In the next years VR devices were mainly used for flight simulation, military training, medical purposes, and automobile design. With the advancements in technology and the launch of an affordable high-quality VR headsets, virtual reality became more accessible for video game players. Today we are witnessing an exciting rebirth of interest in VR, not only in entertainment industry but also in academic research.

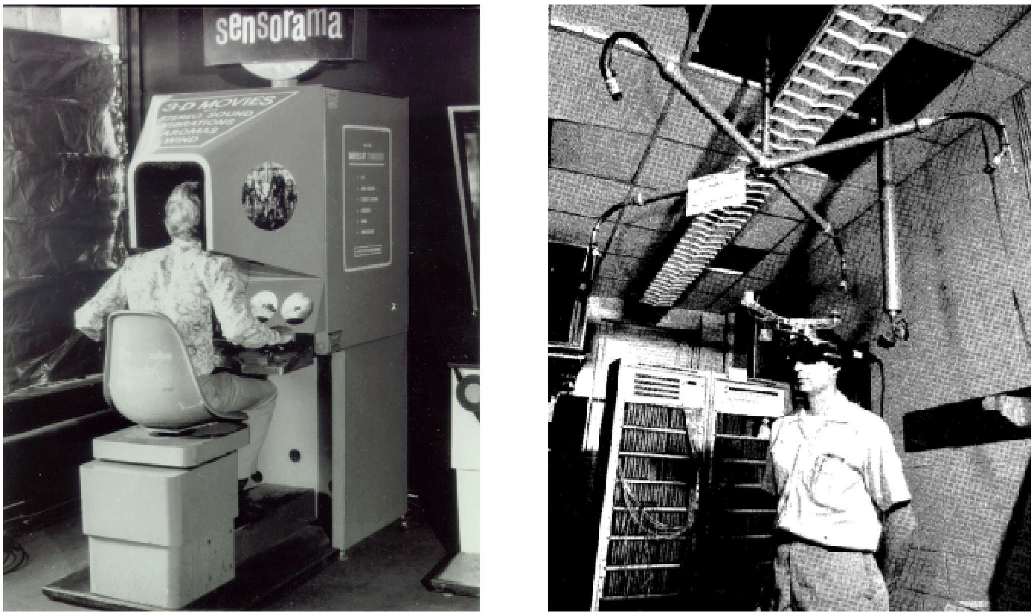

Figure 2.2: The Sensorama and the Sword of Damocles, the first attempts at creating virtual reality (image source: [49][40]).

The renewed interest in VR started in 2012, when a Kickstarter crowdfunding campaign for Oculus Rift (see Figure 2.3) ended with a huge success. The campaign promised an affordable high-quality VR headset to the public, and it received the funding of $250000 in less than 24 hours [4]. Before the final consumer version of Oculus Rift was released on 28 March 2016, the product went through many prototypes: the Development Kit 1, the Crystal Cove, the Development Kit 2, and the Crescent Bay. Over 500 applications were made during the time the two development kits were available for the researchers and campaign's backers. In the following years, other companies developed their own consumer-oriented VR headsets and tried to replicate the success of Oculus Rift. The two big competitors are the HTC Vive and the PlayStation VR. While the Oculus Rift and the PlayStation VR are mainly focused on a seated VR experience, the HTC Vive is specially designed for a room-scale VR experience that allows users to freely walk around a 5m x 5m tracked space. There are also various mobile HMDs, such as the Google Cardboard and the GearVR, that allow using a couple of selected models of smartphones for display and processing of data. The smartphone is inserted into a simple case that keeps it at a short range from the lenses. These devices offer a cheap introduction to VR experience, however, they are not equipped with advanced tracking systems, and they cannot handle more demanding games.

Figure 2.3: Modern popular VR headsets: the Oculus Rift and the Playstation VR (image source: [3][2]).

2.2 VR Input Methods

As more companies enter the VR headset market, we can observe a rapid technological advancement in input devices. Authors of the article *State of the Art of Virtual Reality Technology* [4] identified three different categories for devices handling input in VR: controllers, navigation devices, and tracking technologies. Most of the controllers for VR headsets are hand worn and provide 6DoF (Six Degrees of Freedom) tracking information. They are usually equipped with buttons for discrete input, and top-mounted touchpads or joysticks for analog input. For example, Vive Controller (see Figure 2.4) features 24 sensors, a multi-function trackpad, and a dual-stage trigger [17].

The illusion of traversing an endless space can be achieved with the help of navigation devices. Most devices in this category work similar to traditional treadmills, permitting movement in only one direction. However, some of them allow to move on a two-dimensional plane. For example, Virtuix Omni (see Figure 2.5) is a concave platform with a low-friction surface, which allows locomotive motion in any direction. There are

Figure 2.4: Modern VR controllers: the Oculus Touch and the HTC Vive Controller (image source: [4][17]).

also attempts at creating devices less expensive and more affordable to general public. Google is currently working on motorized shoes that allow an endless movement in a limited space [9]. Other researchers experiment with devices that were not specially designed for virtual reality. For instance, A. Aguirre in his master thesis [1] describes the process of navigation in VR through leaning on the Wii Balance Board.

Figure 2.5: Omnidirectional treadmills: the Virtuix Omni and the WalkMouse (image source: [4]).

There are currently two approaches for motion tracking technologies. First is full body tracking, which focuses on posture and upper body of the users. Second is gesture tracking, which is usually achieved optically or with devices worn on hands. Full body tracking is commonly implemented using magnetic tracking or Inertial Measurement Units (IMUs), providing six degrees of freedom by placing orthogonally to each other accelerometers, gyroscopes, and magnetometers. IMUs are used to perform rotational tracking for the controllers and HMDs. They measure the rotational movements of the yaw, pitch, and roll. Valve came up with different approach, their inside-out Lighthouse tracking system involves two Base Stations that scan the tracked space with lasers [18]. These Base Stations (see Figure 2.6) are small cube-shaped devices placed in opposite sides of the room. They constantly sweep the area with non-visible lights that the receptors on the

HMDs and controllers intercept. The stations serve as reference points for these tracked devices, allowing them to figure out where they are in the 3D space.

Gesture tracking can be achieved with numerous input devices that are not necessarily designed for VR. For example, the Leap Motion technology is designed to track hands and fingers with low processing power, high accuracy, and near-zero latency [28]. It uses three infrared LEDs and two monochromatic IR cameras to observe a hemispherical area up to a distance of about 1 meter. The Leap Motion controller can be attached on top of any virtual reality headset. There are also various sensor technologies designed to be worn like a glove. Besides tracking gestures such as bending of fingers, they sometimes offer additional functionality. One of these data gloves called Gloveone allows users to feel and touch any virtual object that they can see in VR headsets [22]. There are 10 actuators distributed along the fingertips and palm of the glove, which vibrate independently at different intensities and frequencies, reproducing touch sensations.

Figure 2.6: The Vive Base Stations: laser-based tracking system (image source: [18]).

2.3 VR Sickness

While VR is a promising technology, which quickly gains on popularity, it still has a great challenge and safety issue to overcome. Virtual reality sickness (also called cybersickness) is a group of unpleasant symptoms that can occur during an exposure to virtual environment. These symptoms can last from few minutes to even days. They most often include headache, disorientation, sweating, eye strain, fullness of stomach, pallor, vomiting, nausea, dryness of mouth, vertigo, or ataxia [33]. Although similar to motion sickness, VR sickness is different in that it can occur with visual stimulation alone. Motion sickness is mainly induced with vestibular stimulation, while vision can be a contributing cause. It is also sufficiently different from simulator sickness that tends to occur as a result of oculomotor disturbances, with disorientation being the main symptom of VR sickness [39]. Beyond the sickness itself, these undesirable symptoms may have other consequences. VR sickness can reduce the efficiency of VR training and rehabilitation tools, and it can even discourage users from trying virtual reality ever again. Currently, there are many speculations as to why VR sickness occurs. J. J. LaViola in his article about cybersickness [27] describes three following main theories:

- *The sensory conflict theory*: The most commonly accepted theory. It is based on the assumption that inconsistency between the vestibular and visual sense cause a perceptual conflict within the body. These sensory conflicts may appear when the sensory input is not the stimulus that the user expected based on his prior experience. Taking this into consideration, the symptoms of VR sickness could be reduced if the sensory information causing self-motion are in agreement with each other.

- *The poison theory*: The theory tries to explain VR sickness from an evolutionary standpoint. It is based on the premise that the consumption of poison leads to physiological problems, temporarily affecting the coordination of sensory information. Nausea and vomiting serve as an early warning system that may increase the chances of survival. The conflicting stimulation found in VR can cause the misreading of sensory inputs, and it can make the body think that it has been poisoned.

- *The postural instability theory*: This theory focuses on the concept that the main objective of human body is to sustain postural stability at all times. If the control cannot be maintained, the motion sickness symptoms appear. In many virtual environments, there are some optically specified movements that are abnormal for inexperienced users. As a result, their postural control strategies may fail.

There are also other contributing factors to VR sickness, not necessarily related to any of these three theories. Various technical aspects can have a great impact on sickness symptoms, such as a mismatched motion, low refresh rate, or not achieving a target frame rate. Head position tracking is a vital element of any virtual environment, however, current tracking systems are not completely accurate. They can report information with error that leads to uncontrollable movement and dizziness. Studies have shown that increasing a field of view (FOV) tends to increase VR sickness symptoms. Implementing methods to dynamically restrict FOV can help combat this effect [11]. Several other techniques are used to prevent VR sickness. For example, introducing static visual background (see Figure 2.7) allows users to register a verification of their senses while they observe the full locomotion of virtual environment. It has also been noted that some individuals are more susceptible than others to VR sickness [23]. Age, health, postural stability, gender, experience with the system, and many other factors can contribute to the severity of the symptoms.

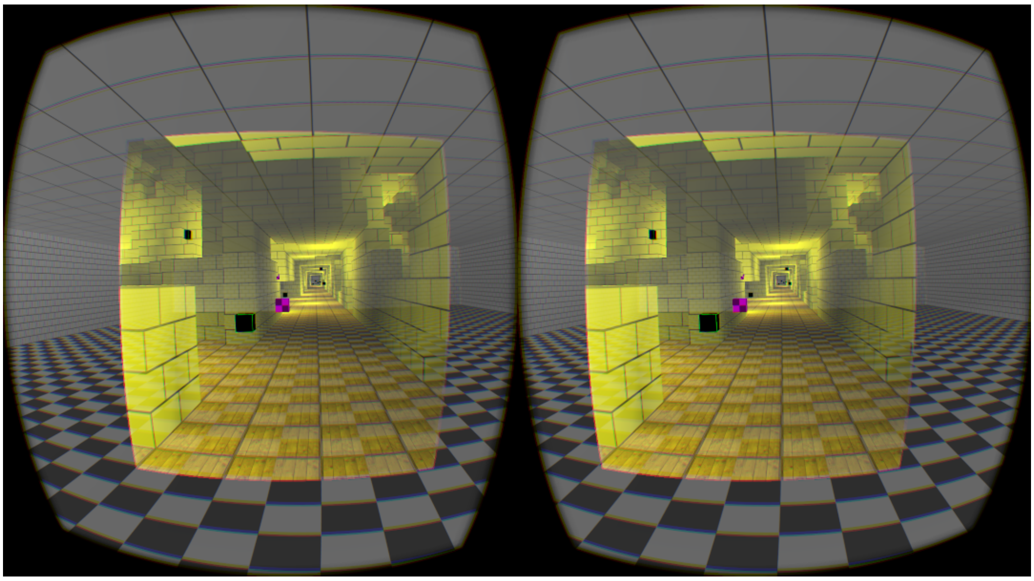

Figure 2.7: Static visual background, a technqiue used to reduce VR sickness symptoms (image source: [15]).

2.4 Locomotion in VR

Implementing locomotion in virtual reality is one of the biggest challenges of a creating comfortable and immersive VR experience. Poorly designed movement, such as sudden unexpected accelerations and rotations, can quickly induce sickness on even seasoned VR users. With the recent advancements in VR technology, numerous new locomotion techniques have been developed and researched [7]. Unfortunately, there still has not been found the perfect approach that would work with equal efficacy across all users. Various methods have their strengths and weaknesses in terms of user experience, immersion, and input devices.

In 2017, C. Boletsis published a systematic literature review [6] of recent studies investigating current VR locomotion techniques. In the 36 articles relevant to the research topic, he has identified the following 11 different methods of locomotion.

- Arm swinging: The user stays in place and swings his arms. Body tracking devices or hand-worn controllers detect the arm movements that are then used to control VR locomotion.

- Chair-based: This technique uses a stool chair as an input device. While sitting on it, the user can tilt and rotate the chair. These registered inputs are translated into VR forward, backward, and sideways motions.

- Controller/joystick: The traditional input devices of video games. Using buttons for discrete input or joysticks for analog input, the user controls the movement in VR.

- Gesture-based: Making hand gestures, such as push and tap, move the user in the virtual environment. Motion sensing input devices track the gestures that are translated into virtual movement.

- Head-directed: The user controls locomotion with the help of equipped HMD. Yaw, pitch, or roll head motions command the direction and speed of VR movement.

- Human joystick: This method uses a sensing board (e.g., Wii Balance Board). By leaning on it, the user can produce the backward, forward, and sideways motions.

- Real-walking: While the user moves freely within a limited physical space, body tracking devices are used to determine his position in the virtual environment.

- Redirected walking: The user explores a virtual world that is significantly larger than the limited physical space. This approach introduces a subtle mismatch between virtual and real movements to wrap the enormous virtual environment into the tracked physical space.

- Reorientation: As in the case of the redirected walking, the user physically walks without restrictions while exploring the unlimited virtual world. This technique modifies the rotational gain of the user. The modification forces him to unknowingly reorient himself when he meets the boundaries of the physical space.

- Teleportation: By making a pointing gesture or using a controller, the user indicates where he wants to move in the scene. He is then immediately teleported to the new location he has just pointed with the controller.

- Walking-in-place: The user makes a walking motion. Input is registered with motion trackers or with the help of treadmill-like navigation devices.

In his literature review, C. Boletsis proposes locomotion typology with four different classification categories (see Figure 2.8). The first of them is an interaction type. It focuses on the methods of triggering VR navigation. Artificial methods utilize various input devices, while physical methods exploit motion cues with body tracking devices. Next category, a VR motion type, separates techniques into continues and non-continues motions. Continues motion offers a smooth, uninterrupted movement, whereas non-continues motion provides instantaneous teleport transitions. A VR interaction space is the third classification category. It can be limited due to the constraints of the physical environment, or it can be open and support the unlimited movement in the virtual environment. Lastly, the techniques can be classified into four distinct VR locomotion types:

- Motion-based: These locomotion techniques support the continuous movement in open interaction space with some kind of physical motions. This type includes methods such as the arm swinging, gesture-based, redirected walking, reorientation, and walking-in-place locomotion.
- Room scale-based: The techniques that support continuous movement and utilize interaction with physical movement. However, as opposed to motion-based methods, the interaction space is limited by the physical environment's size. From the previously mentioned techniques, only the real-walking locomotion matches this description.
- Controller-based: The methods under this type use various controllers for continues movement in open interaction spaces. Locomotion techniques such as the human joystick, chair-based, head-directed, and joystick-based fall under this type.
- Teleportation-based: This locomotion type uses artificial interactions in open interaction spaces. It differs from the controller-based methods in the non-continues movement, as the user is immediately teleported to the selected position. This type includes the free and fixpoint teleport techniques.

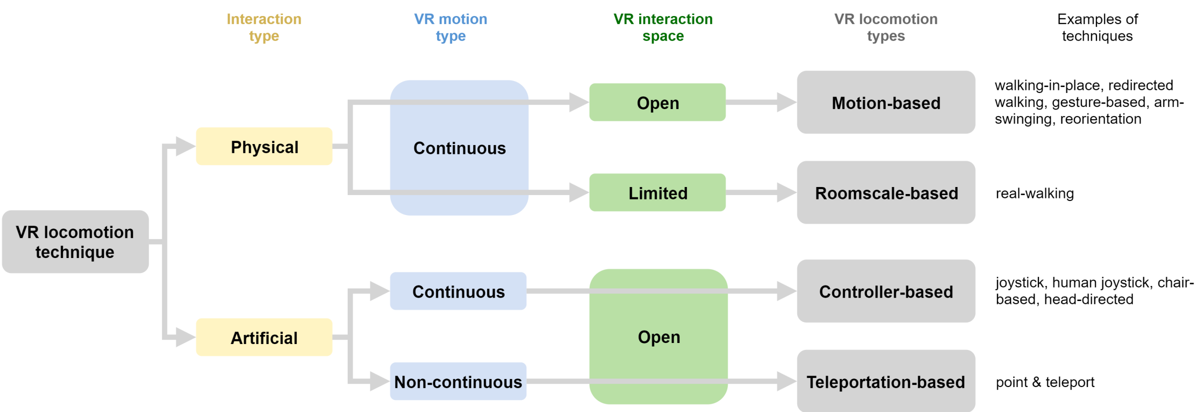

Figure 2.8: The VR locomotion typology (image source: [6]).

Although there are many promising solutions to VR locomotion, currently only a handful of them are used in mainstream VR games. Approaches like the real-walking, reorientation, or redirected-walking locomotion offer creative way of exploring the virtual world, however, they often require a dedicated and expensive hardware, large tracking space, and can be tiring in longer VR sessions. For these reasons VR developers mostly implement regular controller-based locomotion techniques. Unfortunately, the joystick-based continuous motion is known for inducing VR sickness symptoms. This problem is now partly solved with effective dynamic field-of-view adjustments [11]. Many popular VR games, such as Robo Recall, Raw Data, and Vanishing Realms, adopt a "Point & Teleport" locomotion to reduce the effects of motion sickness [19]. This technique uses a pointing curve as the indicator for the teleportation path (see Figure 2.9). Although it has been proved by some researchers to be the least discomforting locomotion method for VR users, its drawback is that it can also reduce a sense of presence within VR environment [12]. An alternative fixpoint teleport locomotion, which allows the player to quickly move between predefined node positions, can be applied to preserve accessibility while maintaining the feeling of presence [14].

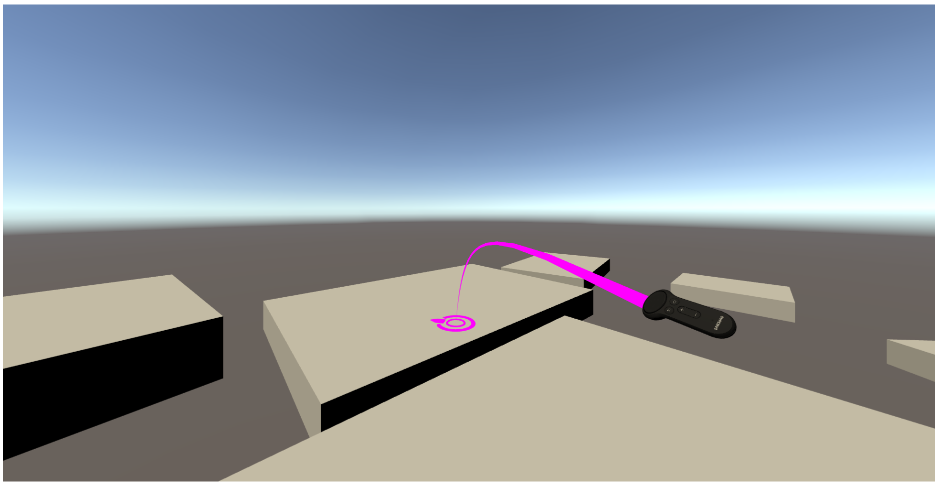

Figure 2.9: The Point & Teleport locomotion technique that uses a curve as the indicator for the teleportation path (image source: [41]).

There are several tricks and best practices for designing VR locomotion. Oculus in their developer documentation [31] lists general guidelines for acceleration, speed, user control, and direction of locomotion. Accelerations in VR not initiated by the user's physical movement are the main cause of discomfort. It is best to avoid any unpredictable increases of the size, frequency, and duration of the acceleration. Manipulations of speed, such as a slow-motion or unnaturally rapid velocity, have been reported to be less discomforting than a normal human pace. In the real world, humans most often move forward or stand in place. When the VR movement is necessary, it is best to prevent backing up or strafing movements as it can be unusual optic flow pattern to the users. Open environments are also generally more comfortable. Moving the users through enclosed spaces, such as tunnels or hallways, should be avoided.

2.5 Problem of VR Head Collisions

Although modern VR games use different techniques to move the player's avatar in the virtual environment, most of them have one thing in common. They use tracking systems to estimate the position and rotation of the user's head. The player now gets the ability to look around the virtual world with physical head movements without the need of additional input controllers. Head tracking increases the feeling of presence in virtual reality. It also drastically reduces VR sickness symptoms that are caused due to the mismatch between vestibular and visual senses [20]. However, the positional head tracking introduces a significant problem with head-object collisions in the virtual scene.

In traditional video games, a virtual camera used to render a game world is under full control of the game logic. It usually follows the player's avatar in a first-person or third-person view, or it is set during the game creation to some fixed position and orientation. The game engine then renders an image of the virtual world for that camera setup. For the most part, video games use collision detection systems to prevent the intersection of two or more objects on the game scene. If the player collides with some game object, such as a table or wall, the player's avatar and the camera stop moving in that direction. The user is under the impression that he has been physically blocked by the object.

With the addition of head tracking to VR games, some of the camera control rules change or become obsolete. Almost all VR games are playable only in the first-person view. This makes the players feel immersed and present in the virtual world. The camera's position still follows the avatar's head, but the camera's rotation is now set using the player's real-world head rotation. Unfortunately, head tracking also changes the way how head-object collisions are normally resolved in games. The problem arises when the player's head should collide with some game object, but the user keeps moving his head in real-world without any obstructions. There are researchers that experiment with a haptic system that can simulate walls or heavy objects via electrical muscle stimulation [29]. However, it could take years before this technology works properly and becomes available to the mainstream VR users. With the recent popularity of VR games, there is a need for solution that could be adapted by current VR developers.

Figure 2.10: In the game Fallout 4 VR, players can see through walls when they lean against them (image source: [37]).

Many developers ignore the problem of head collisions and decide to not handle it in any way [32]. If the player positions himself close to some obstructing object in the virtual scene and then starts leaning in the direction of the collision, the head rotation will still update according to the real-world position. The player will be able to look inside or past the colliding object. This results in unexpected clipping artifacts (see Figure 2.10) that break the feeling of presence in virtual world. The ability to see through the game objects can also have undesirable effects on game mechanics. In games with the Point & Teleport locomotion, the players can cheat by teleporting through walls to skip harder game areas [5]. In shooter games, the players can see and shoot through walls, giving them an unfair advantage over enemies. There is a need for solution that would at least restrict the forbidden view. For these reasons, many VR developers try various techniques for handling head collisions in their games. The most commonly used methods are:

- Screen fade: When the head collision is detected, the screen slowly fades to black or any other solid color (see Figure 2.11). The view remains blacked-out for as long as the player's head collides with the object. Because this technique is relatively simple to implement, it attracts many VR developers looking for a quick solution to the problem. However, the method has one weakness that makes it not work well with the Point & Teleport locomotion technique. For example, the player can unintentionally teleport to some head-object colliding position. He is then stuck in a black void, without knowing in what direction he should move his head to escape the darkness.

- Delayed push-back: If the player collides with some object for a couple of seconds, he is gradually pushed backwards until he leaves the object's boundaries. This method is often used in older open-world games that were nowadays ported to VR, such as Skyrim VR or Fallout 4 VR. In most implementations of this technique, the head tracking is completely disabled during the duration of the push-back effect. Many players of these games reported that the camera push-back is frustrating to experience and makes them feel dizzy [37][35][34]. The reason is that the push-back effect takes control of camera movements away from the player, which tends to increase VR sickness symptoms.

- Instant push-back: In this solution, the collisions are handled similarly to how they are handled in most non-VR games; the player's virtual body, including the head, is never able to get past virtual walls and other obstacles. When the user collides with some obstacle, a collision vector is computed and its projection on the horizontal plane is added to the player's position. This effectively moves the user away from the object, preventing him from ever looking inside it. If the player decides to keep moving his head forward, despite the fact that there is a virtual wall in front of him, he will feel like he is using his head to push himself backwards from the wall. In 2018, a group of researchers [51] experimented with this technique, which they called a "not there yet" approach. The researchers compared this solution to the screen fade method in terms of immersion and VR sickness. Unfortunately, they found out that while the "not there yet" approach yielded better immersion results, it contributed more to VR sickness symptoms.

- Teleportation: If the collision is detected and maintained for a couple of seconds, the player is teleported to a nearby collision-free location. This method works similarly to delayed push-back, but instead of gradually moving the player away from the obstacle, he is instantly teleported to the last know valid position. Virtual Reality Toolkit, a collection of useful concepts and scripts that aid building VR applications, offers an implementation of this method that can be adjusted by many parameters [48]. For example, developers can set the amount of time for the teleportation delay or the additional push-back distance, which prevents the player from being right next to the obstacle again after the teleportation occurs.

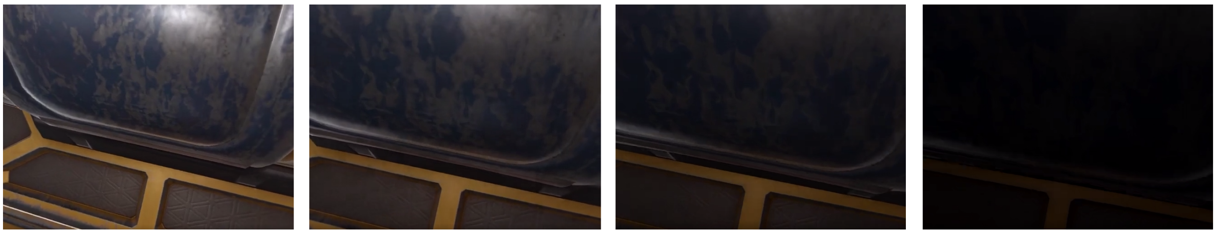

Figure 2.11: A time slice example of the screen fade technique. When the head collision is detected, the screen slowly fades to black (image source: [36]).

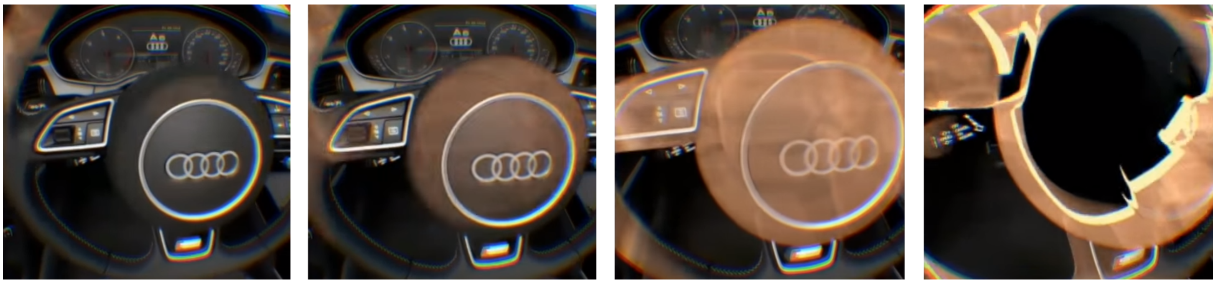

Figure 2.12: A time slice example of the object fade technique. The closer the camera gets to the collision, the more the colliding object is faded out (image source: [50]).

Sometimes the solutions mentioned above are slightly modified to fit the aesthetic of the game. For instance, the solid color in the screen fade technique can be replaced by any image or virtual scene. There are also some other, less popular ideas for solving the head collisions problem. Object fade is a technique in which, rather than fading the whole screen to black, only parts of the colliding objects fade out as the camera gets closer to them (see Figure 2.12). The advantage of this solution is that the player can easily recognize which specific objects are colliding with him. If he unintentionally teleports to some head-object colliding position, he can maneuver his head out of the highlighted objects. He can also completely avoid any collisions by tracking the color of surrounding obstacles. If some object starts to fade, the player knows to not get any closer to it.

Some VR developers try completely different approach by designing the whole gameplay around collisions. The virtual environment is carefully designed in the way that prevents the players from colliding with any object in the game. The problematic collisions are then avoided all together by restricting the movement to only specific game areas. In other VR games, the collisions are the main objective of the gameplay. The central mechanic is to collect or destroy some objects that disappear when they collide with the player, making it impossible to look inside them [10].

2.6 Conclusion

In recent years, there has been growing interest in VR technology. Modern VR headsets offer an affordable VR experience that is easy to set up in a home setting. The HTC Vive aims at providing immersive room-scale VR, whereas other companies focus on seated experience that does not require a large tracking space and additional inside-out tracking devices. The hand worn controllers, which support 6DoF tracking information, are the current standard for handling input in almost every VR system. They track the movement of the user's hands, allow him to pick up objects in the virtual world, and are useful in many locomotion techniques. In the Point & Teleport technique, they allow for an easy manipulation of the teleportation curve. Most often, VR headsets are also equipped with some sort of the head tracking system. Head tracking greatly increases the feeling of presence in virtual world and reduces the symptoms of VR sickness.

The commercial success of VR headsets has brought the attention of many academic researchers. There have been a lot of studies into comfortable and immersive locomotion techniques that can be used in virtual reality. VR experience is often measured using questionnaires about the satisfaction of being in VR, the sense of presence in VR, and the symptoms of simulator sickness. The consensus is that the teleportation methods are best suited for the seated VR experience in terms of usability and preventing VR sickness. Although the topic of locomotion is widely studied, researchers have not treated head tracking in much detail. Apart from the recent study about "not there yet" approach, there is almost no academic work on the problem of VR head collisions. This thesis examines the most popular methods for solving the problem and tries to propose the best solution.

Chapter 3

Method

3.1 Research Questions and Hypotheses

There is a general lack of research into the problem of VR head collisions. Current VR developers experiment with various solutions in their games, and all of these methods have their advantages and disadvantages. There is a disagreement in VR developers community over which solution should be used in future games. Some developers wonder if it is even worth the effort to implement any solution at all. Therefore, the goal of this study is to examine different solutions and to determine which one of them is best suited for modern VR games.

There are several possible solutions to the problem of VR head collisions, and they can be implemented in many different ways. Due to time constraints, only the following four most popular methods were chosen for this study:

- Screen fade: When the head collision is detected, the whole screen fades to black in the span of a second. The view remains blacked-out for as long as the player's head collides with the object.
- Delayed push-back: If the player keeps colliding with the object for longer than a second, he is slowly pushed backwards until he leaves the object's boundaries.
- Instant push-back: When the user starts to collide with some obstacle, a collision vector is computed and its projection on the horizontal plane is immediately added to the player's position. This effectively moves the user away from the object, preventing him from ever looking inside it.
- Teleportation: If the collision is detected and maintained for the duration of a second, the player is instantly teleported to the last known valid position.

The quality of VR experience is affected by many factors. VR sickness, the sense of presence in virtual world, and the usability of the user interface are some of the main considerations in designing comfortable VR experience. Some developers consider different factors to be more important than others. For this reason, the proposed solutions to the problem of VR head collisions are examined from three different perspectives. The answers to the following research questions will help VR developers decide which particular solution to use:

- RQ1: How the proposed solutions to the problem of VR head collisions affect virtual reality sickness?

- RQ2: How the proposed solutions to the problem of VR head collisions affect the sense of presence?
- RQ3: How usable are the proposed solutions to the problem of VR head collisions?

Three null hypotheses corresponding to the research questions are as follows:

- H_{01}: All proposed solutions to the problem of VR head collisions have the same effect on virtual reality sickness.
- H_{02}: All proposed solutions to the problem of VR head collisions have the same effect on the sense of presence.
- H_{03}: All proposed solutions to the problem of VR head collisions have the same level of usability.

The null hypotheses are tested against the following three alternative hypotheses:

- H_{A1}: Some proposed solutions to the problem of VR head collisions have more positive effect than others on virtual reality sickness.
- H_{A2}: Some solutions to the problem of VR head collisions have more positive effect than others on the sense of presence.
- H_{A3}: Some solutions to the problem of VR head collisions have higher level of usability than others.

3.2 Questionnaires

Two questionnaires were prepared for the study. Before the experiment began, participants were asked to fill in a demographic questionnaire. It included information about age, gender, previous experience with VR, and previous experience with motion sickness (see Appendix A). Each time after testing one of the solutions to the problem of VR head collisions, the participants filled in a post-test questionnaire (see Appendix B). This questionnaire is composed of three sections, which correspond accordingly to the three research questions. First, the participants described what VR sickness symptoms they felt during the experiment (see question 2 in Appendix B). Next, they answered to six questions about the sense of presence in the virtual environment (see questions 3-8 in Appendix B). Finally, the participants rated the tested method with eight usability factors on the scale from 1 to 5 (see question 9 in Appendix B).

3.2.1 Simulator Sickness Questionnaire

The VR sickness section of post-test questionnaire was prepared using the Simulator Sickness Questionnaire (SSQ) [21], a widely acknowledged standard for studying simulator sickness. The SSQ was developed in 1993 with the purpose of enhancing training efficiency in flight simulators. Due to the similarity of simulator sickness with VR sickness, in the recent years the SSQ was also used by many researchers studying comfortable VR locomotion [12][14][25]. The SSQ consists of 16 most commonly occurring simulator sickness symptoms: general discomfort, fatigue, headache, eye strain, difficulty focusing, salivation increasing, sweating, nausea, difficulty concentrating, "fullness of the head", blurred vision, dizziness with eyes open, dizziness with eyes closed, vertigo, stomach awareness, and burping. These symptoms fall into three different categories: nausea-related, oculomotor-related, and disorientation-related. Each questionnaire item is scored on a four point scale (0-3): none, slight, moderate, and severe. The scores for each category and the total SSQ score are multiplied by the following weight factors: nausea is multiplied by 9.54, oculomotor by 7.58, disorientation by 13.92, and total SSQ by 3.74.

3.2.2 Presence Questionnaire

The Slayer-Usoh-Steed (SUS) [45] presence questionnaire was used to prepare the second section of post-test questionnaire. It was chosen for this study because it is the second most cited presence questionnaire applicable for VR [38], and it has a relatively short list of six questions in comparison to other, longer questionnaires. All SUS questions are based on one of the three themes: the extent to which the virtual environment becomes the dominant reality, the sense of being in the virtual environment, and the extent to which the virtual environment is remembered as a “place”. Each question is answered on a scale from 1 to 7, where the higher score indicates the greater sense of presence. The final presence score is a number of answers that have a score of 6 or 7.

3.2.3 Usability Questionnaire

In the usability section, the participants rated eight different factors: difficulty in understanding the method, difficulty in operating the method, feeling of being in control while using the method, required effort to use the method, feeling of tiredness while using the method, feeling of enjoyment while using the method, feeling of being overwhelmed while using the method, feeling of frustration while using the method. This exact approach was also used in two recent VR locomotion studies [8][14]. Each question was answered on a 5 point Likert scale, where 1 meant “not at all” and 5 meant “very much”. The total usability score was calculated as follows: for each factor, except for the “feeling of being in control” and “feeling of enjoyment”, the score was firstly subtracted from 5, and then it was added to the total score. In the two mentioned cases, the factor score was firstly subtracted by 1, and then it was added to the total score.

3.3 Implementation

The virtual environment used in the experiment was implemented using the Unity game engine (version 2018.3.6) [44]. Unity is a cross-platform engine that allows creating high-quality 3D games and natively supports VR development. The SteamVR Unity Plugin (version 1.2.3) [13], a software development kit and application programming interface developed by Valve, was used to smoothly interface virtual reality headset with Unity. The plugin manages the following functions: loading 3D models for VR controllers, handling input from the controllers, and estimating what the hands look like while using those controllers. Additionally, the application used some functionality of the Virtual Reality Toolkit (VRTK) (version 3.3.0) [46]. VRTK is a collection of useful design patterns and pre-built assets that aid solving common problems found when building for virtual reality. It covers common solutions for locomotion within virtual space, interactions with virtual objects and UI elements, body physics, and much more.

3.3.1 Virtual Environment

The virtual environment consisted of a large (30m x 30m), blue platform with 10 red objects: a box, a ladder, a pallet, a shed, a barrel, and five different trees (see Figure 3.1). The platform was surrounded by short mountains to prevent users from wandering away from the designed experiment area. All 3D objects on the platform were imported from the free package found in the Unity Asset Store [42]. The platform itself was a scaled up cube model found in the default Unity assets. The terrain was generated by the Unity's built-in Terrain Engine.

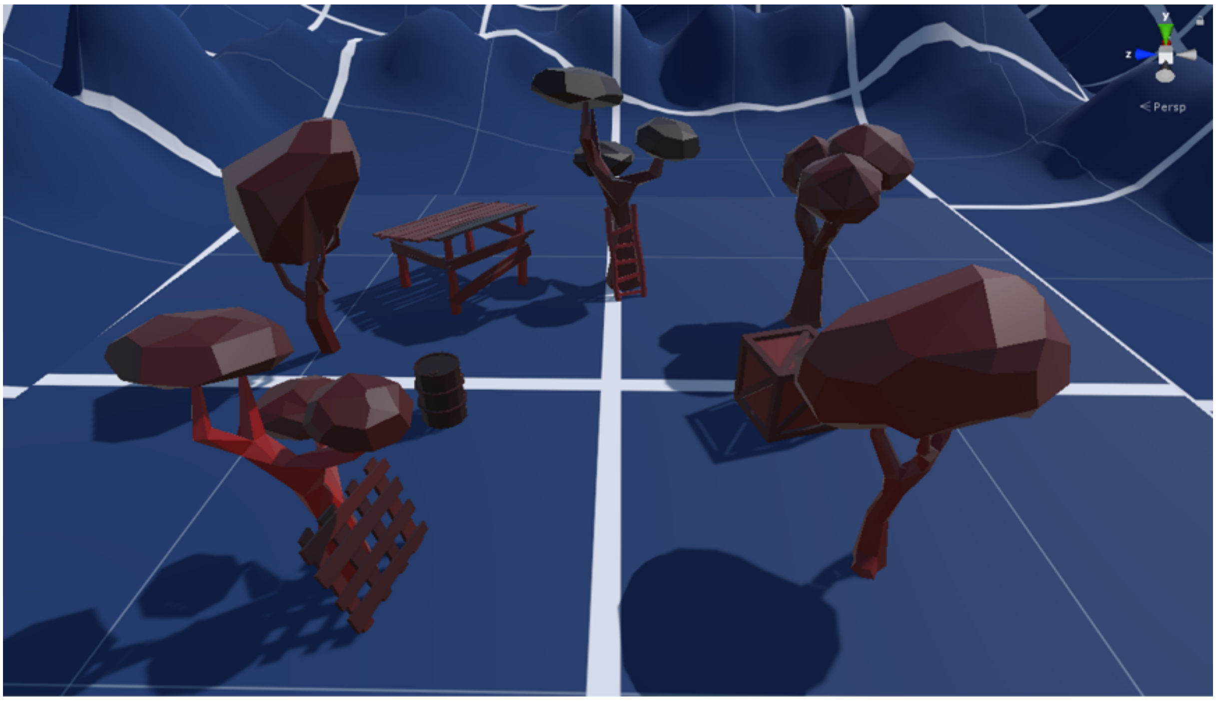

Figure 3.1: The virtual environment used in the experiment: a large platform with 10 various objects on top.

At the start of the application, the user of VR headset was placed in the center of the platform. The user could move through the virtual environment by using the "Point & Teleport" locomotion technique. When the user pressed and held the trackpad on the controller, a blue teleportation curve appeared. He could then teleport by pointing with his hand and releasing the trackpad. The user could only teleport to areas on the platform that were not occupied by the 10 objects. When the area was not viable, the curve's color was changed from blue to red (see Figure 3.2). The teleportation locomotion was implemented with the help of VRTK_HeightAdjustTeleport script [47].

The goal for the user was to teleport closely to one of the objects in the virtual environment. Next, he had to lean his head towards the object with the purpose of colliding with it. Once the collision was detected, one of the implemented solutions to the problem of VR head collisions was activated. Finally, when the user left the object's boundaries due to the workings of the method, the object's color was changed to green. The green color indicated that the interaction with this object was completed successfully. The user had to repeat the process with each one of the 10 objects until every obstacle was turned green. Because of the need to test four different solutions to the problem of VR head collisions, four different virtual environments were prepared for the study. All virtual environments were visually identical to each other, with the same placement of the 10 virtual obstacles. The only difference between them was the method of handling VR head collisions.

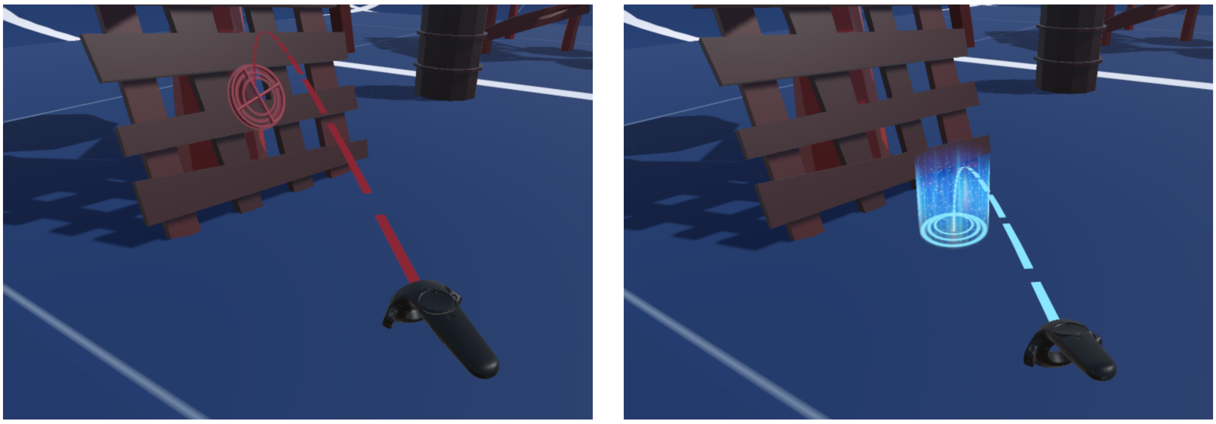

Figure 3.2: The color of teleportation curve was changed from blue to red when the teleportation path was interrupted by one of the objects.

3.3.2 Solutions to the Problem of VR Head Collisions

To detect if the collision with the object occurred, a trigger sphere collider [43] with the radius of 0.1 m was attached to the user's virtual head. For handling head collisions, four different solutions were implemented: screen fade, delayed push-back, instant push-back, and teleportation. The solutions were implemented by replicating the mechanisms seen in popular VR applications. In the screen fade method, the whole screen gradually faded to black in the span of a second when the collision was detected. Once the user left the object's boundaries by retracting his head back, the object's color was changed from red to green, and the screen gradually returned back to normal in the span of a second (see Figure 3.3).

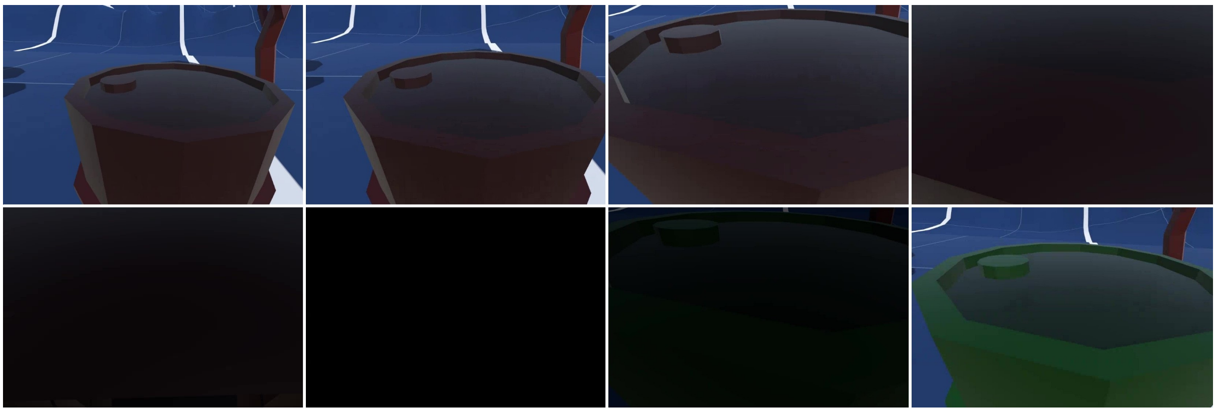

Figure 3.3: A time slice of the implemented screen fade method. The images are ordered from left-to-right and top-to-bottom.

The implementation of the delayed push-back method was more complicated and required more steps. In every frame of the application, the collision-free headset position was saved to a variable if the user was not colliding with any object at the moment. After the collision was detected and maintained for the duration of a second, a collision vector between the last collision-free headset position and the current headset position was calculated. The user's position was then pushed back in the direction of the normalized collision vector with the speed of 1 m/s. The push-back effect was working until the user left the object's boundaries. During the duration of the effect, the head tracking system was fully functional and the user could still move his head in every direction. The color was changed to green once the user left the object's boundaries (see Figure 3.4).

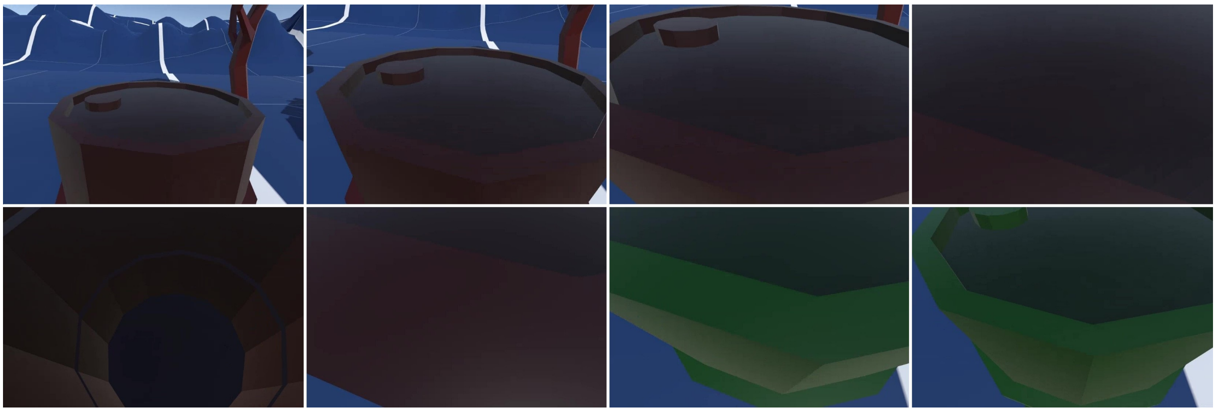

Figure 3.4: A time slice of the implemented delayed push-back method. The images are ordered from left-to-right and top-to-bottom.

The implementation of the instant push-back method was similar to the delayed push-back with a couple of small differences. The collision vector was not normalized, and there was no delay before moving the player's position. In every frame of application, the user was instantly pushed back to the last collision-free position if the collision was detected. To change the color of the object to green, the user had to keep pushing his head in the direction of the collision for the duration of a second (see Figure 3.5).

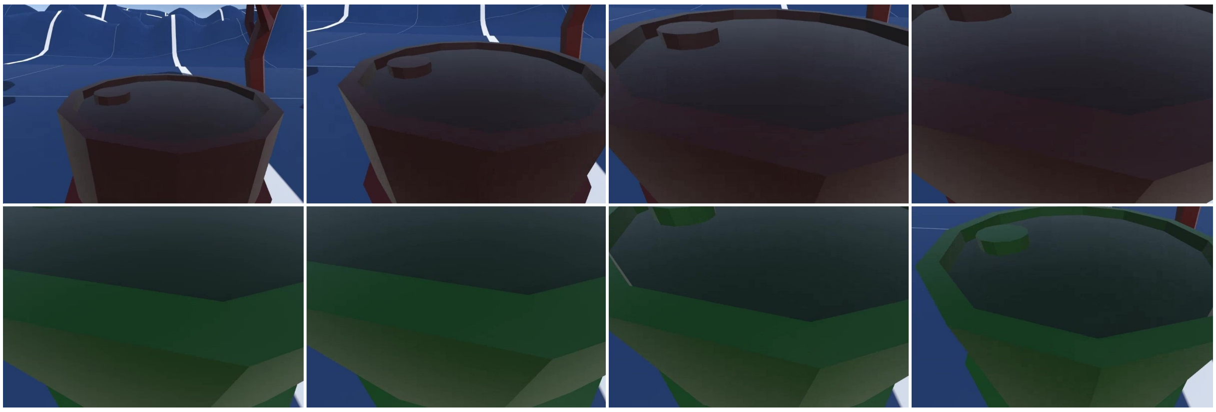

Figure 3.5: A time slice of the implemented instant push-back method. The images are ordered from left-to-right and top-to-bottom.

In the teleportation technique, the collision vector was also not normalized, and this time there was a delay before the method started working. After the collision was detected and maintained for the duration of a second, the screen blinked for a moment to black, and the user was instantly teleported to the last collision-free position. Once the teleportation occurred, the object's color was changed from red to green (see Figure 3.6).

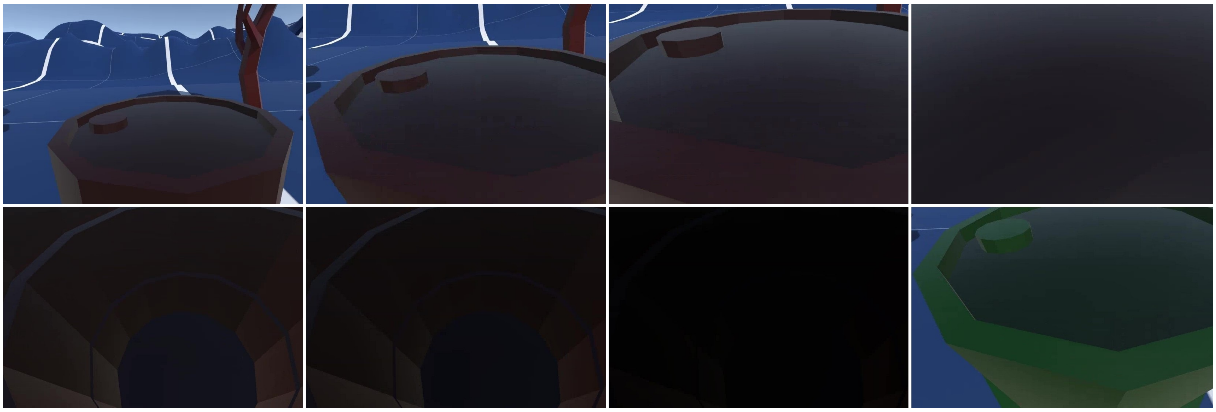

Figure 3.6: A time slice of the implemented teleportation method. The images are ordered from left-to-right and top-to-bottom.

3.4 Experiment

The study employed a within-subject design. The independent variable was the solution to the VR head collisions problem, and it had four levels: screen fade, object fade, camera collider, camera push-back. Due to time constraints, the participants were required to complete the whole experiment with every method in one sitting. For each participant, the order of tested solutions was assigned randomly with Latin Square counterbalancing, where each combination could only be used once.

3.4.1 Equipment

The experiment took place in teaching laboratories with play spaces of approximately 3m x 3m. The participants were equipped with the HTC Vive head-mounted display and its 6DoF hand controller. HTC Vive provides a refresh rate of 90 Hz and a resolution of 2160 x 1200 pixels (1080 x 1200 pixels per eye) with 110° diagonal field of view. Additionally, two Base Stations of the HTC Vive Lighthouse System were used for tracking the head's position and rotation in a 3D environment, which was an integral part of the experiment. A laptop equipped with Nvidia GeForce GTX 1050ti graphic card, 8GB of main memory, and 3.5 GHz Intel Core i5 processor was used for running the implemented VR application. During the experiment, the VR application run at stable 90 frames per second.

3.4.2 Participants

20 participants (3 females, 17 males) aged between 13 and 26 ($M = 19.65$, $SD = 5.29$) were recruited for the study. 12 of them were students of Computer Science master's degree (3 females, 9 males) aged between 23 and 26 ($M = 23.92$, $SD = 1.08$). The rest consisted of children from primary schools (8 males) aged between 13 and 14 ($M = 13.25$, $SD = 0.46$). 9 participants reported that they never experienced motion sickness. This group was particularly instructed about the symptoms of VR sickness. 40% of the participants have never used a VR headset before and were instructed in details how to use one. See Figure 3.7 for additional charts illustrating the background of the participants.

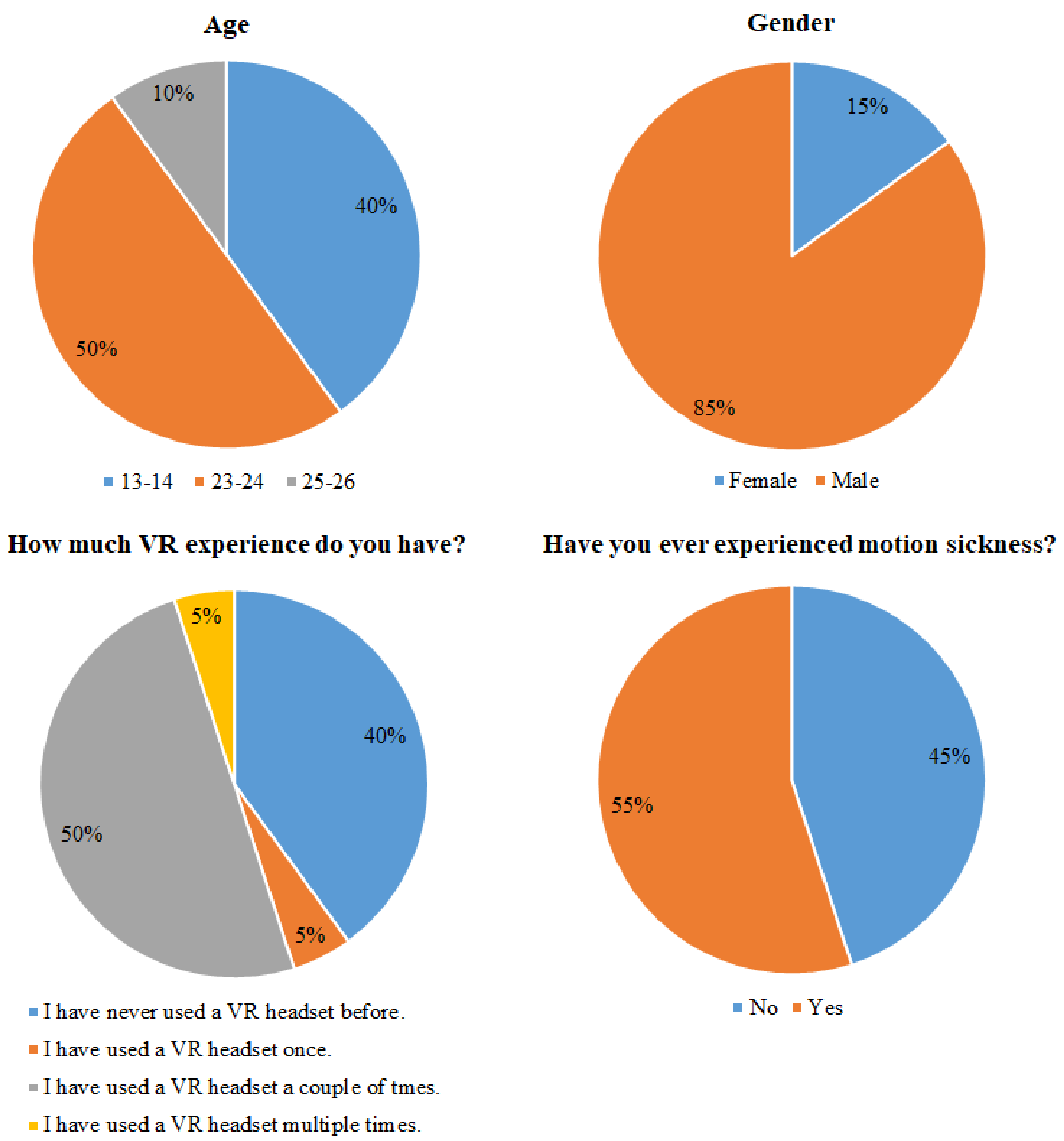

Figure 3.7: A couple of pie charts illustrating the background of the participants.

3.4.3 Procedure

Upon arriving in the teaching laboratory where the experiment took place, the participants were given a broad overview of the research problem. They were introduced to the main goal of the study and instructed about the task they had to do while present in the virtual environment. Because only a single HTC Vive equipment was available, the participants had to take turns to complete the experiment. Before equipping the headset, the participants were asked to fill in a demographic questionnaire (see Appendix A) about age, gender, previous experiences with motion sickness, and previous experiences with VR headsets.

Once the participant finished filling in the demographic questionnaire and was acquainted with the instructions, he equipped the headset and started testing one of the solutions to the problem of VR head collisions (see Figure 3.8). His assigned task was to collide with every obstacle in the presented virtual environment. The participant was not told which solution he is testing, and he had to discover on his own how the method is working. Once he successfully collided with the object and observed the effects of the method, the obstacle's color was changed from red to green.

The participant tested the method until every obstacle in the virtual environment was turned green. On average, it took the participants 2.37 ($SD = 0.62$) minutes to complete this task. Once done, the participant was asked to take off the headset and fill in a post-test questionnaire (see Appendix B). In this questionnaire he described what VR sickness symptoms he felt during the experiment, answered to six questions about the sense of presence, and rated the tested method with eight usability factors. Once the post-test questionnaire was finished, the participant moved on to test the next method. He repeated this process until each of the four methods were tested in this manner. Every participant tested the methods in a unique order.

Figure 3.8: The participants were equipped with the HTC Vive headset and its 6DoF hand controller.

Chapter 4

Results

The results chapter is split into three parts to match the sections of the post-test questionnaire: VR sickness (see question 2 in Appendix B), presence (see questions 3-8 in Appendix B), and usability (see question 9 in Appendix B). This study employed a repeated measures design, where each of 20 participants tested in succession all four solutions to the problem of VR head collisions. For each solution, 20 results were gathered from the questionnaires. If the assumptions of normality and sphericity were not violated, the difference between means were analyzed at 0.05 level of significance using a repeated measures ANOVA; otherwise, a Friedman test was used. The distribution of the data was checked for normality using a Shapiro-Wilk test, and a Mauchly's test was used to assess sphericity. If the results indicated statistical significance, additional post-hoc tests with Bonferroni correction were used to determine which means differed from each other. All tests were performed in MATLAB (version R2015a) [30].

4.1 VR Sickness

4.1.1 Nausea, Oculomotor, and Disorientation

The SSQ nausea, oculomotor, and disorientation scores were calculated and were analyzed using Friedman tests due to non-normality. The method of handling collisions did not significantly influence the SSQ nausea scores ($\chi^2(3) = 4.536$, $p = 0.209$) and the SSQ oculomotor scores ($\chi^2(3) = 7.173$, $p = 0.067$). The test revealed that the SSQ disorientation scores were significantly influenced by the method ($\chi^2(3) = 8.713$, $p = 0.033$). Post-hoc Wilcoxon signed-rank tests revealed that the screen fade method led to significantly lower scores than the delayed push-back method ($p = 0.017$). See Figure 4.1 for an overview of the SSQ nausea, oculomotor, and disorientation scores.

4.1.2 Total SSQ Scores

The total SSQ scores were calculated and were analyzed using a Friedman test due to non-normality. The test revealed that the total SSQ scores were significantly influenced by the method of handling collisions ($\chi^2(3) = 9.881$, $p = 0.02$). Post-hoc Wilcoxon signed-rank tests revealed that the screen fade method led to significantly lower scores than the delayed push-back method ($p < 0.001$). See Figure 4.2 for an overview of the total SSQ scores.

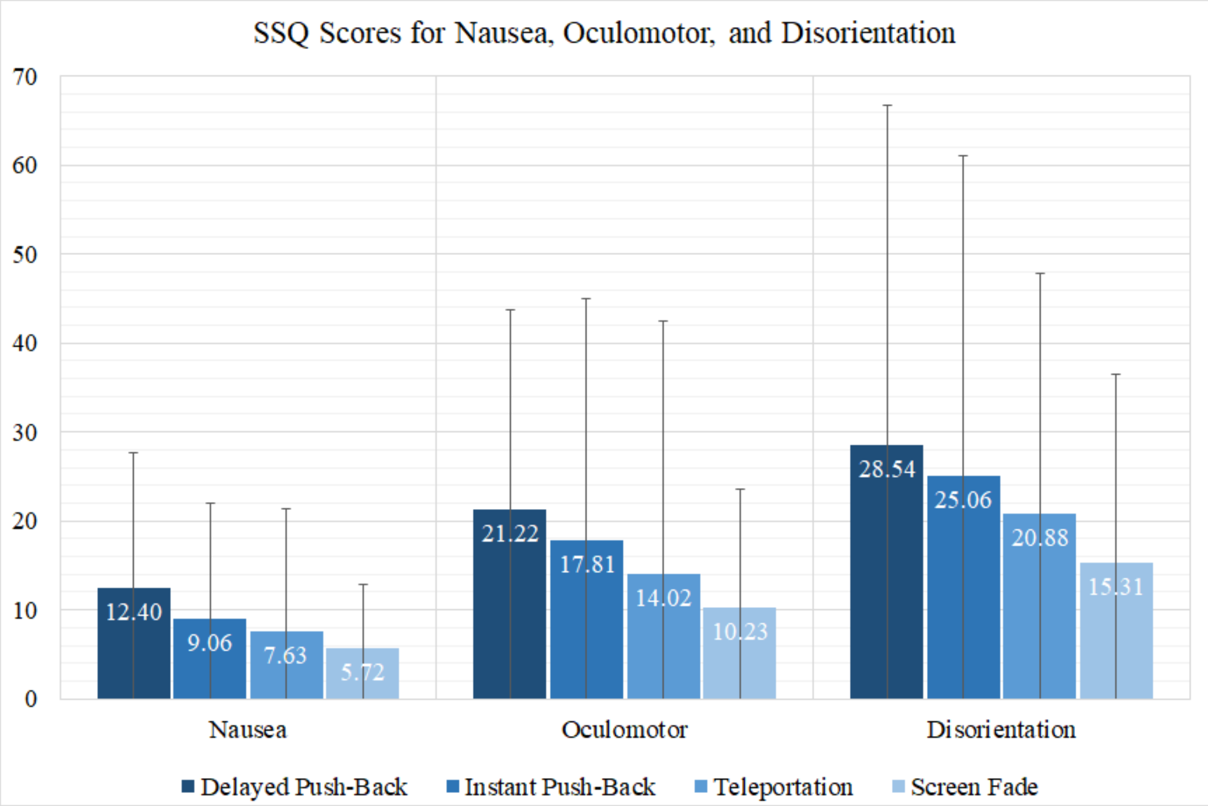

Figure 4.1: The SSQ scores for nausea, oculomotor, and disorientation.

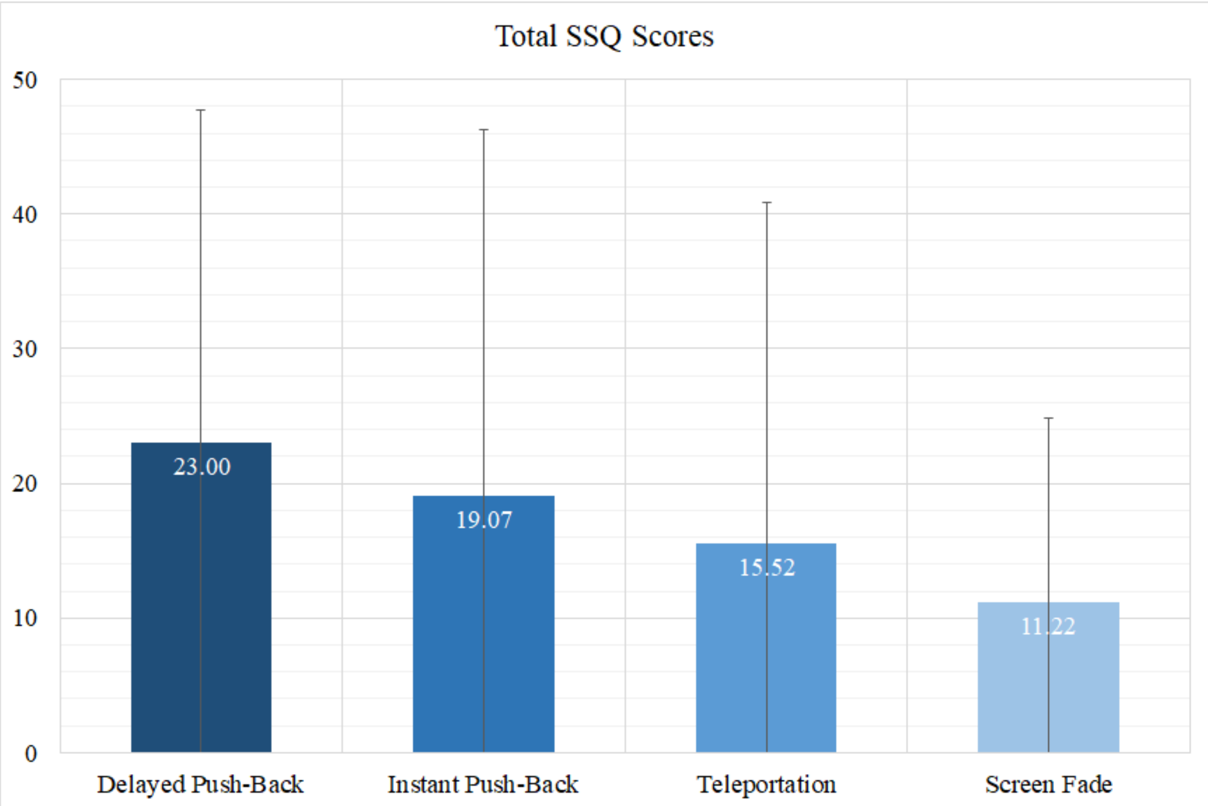

Figure 4.2: The total SSQ scores.

4.2 Sense of Presence

The SUS presence scores were calculated by counting a number of answers to questions 3-8 that have a score of 6 or 7. Shapiro-Wilk tests indicated that the assumption of normality was not violated; and Mauchly's test indicated that the assumption of sphericity was met ($\chi^2(3) = 9.758$, $p = 0.082$). A repeated measures ANOVA revealed that the presence scores were significantly influenced by the method of handling collisions ($F(3, 76) = 11$, $p < 0.00001$). Post-hoc pairwise comparisons revealed higher presence scores for the screen fade method compared to the delayed push-back ($p < 0.001$) and teleportation ($p = 0.002$). The comparisons also revealed higher presence scores for the instant push-back method compared to the delayed push-back method ($p = 0.01$). See Figure 4.3 for an overview of the SUS presence scores.

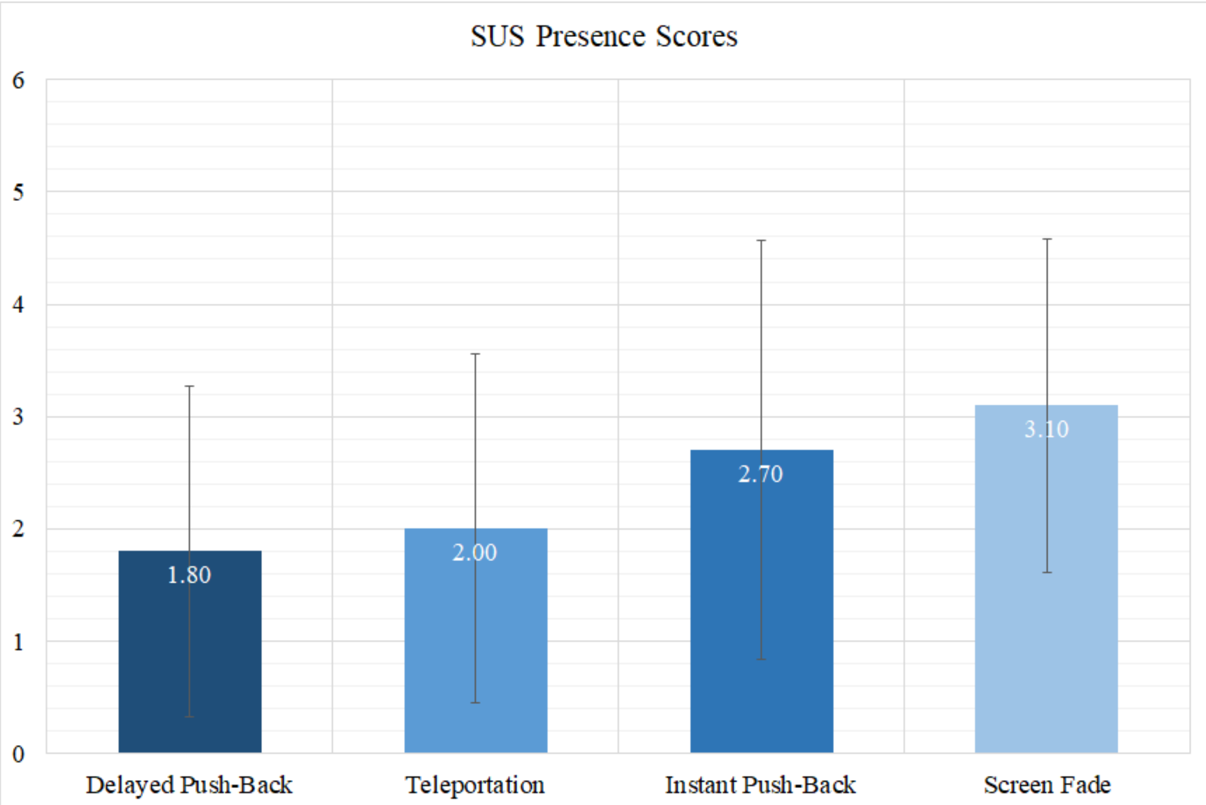

Figure 4.3: The SUS presence scores.

4.3 Usability

4.3.1 Difficulty in Understanding and Operating

The usability scores for difficulty in understanding and operating the method were analyzed using Friedman tests due to non-normality. The method of handling collisions did not significantly influence the scores for difficulty in understanding ($\chi^2(3) = 7.359$, $p = 0.061$) and the scores for difficulty in operating ($\chi^2(3) = 6.788$, $p = 0.079$). See Figure 4.4 for an overview of the usability scores for difficulty in understanding and operating the method.

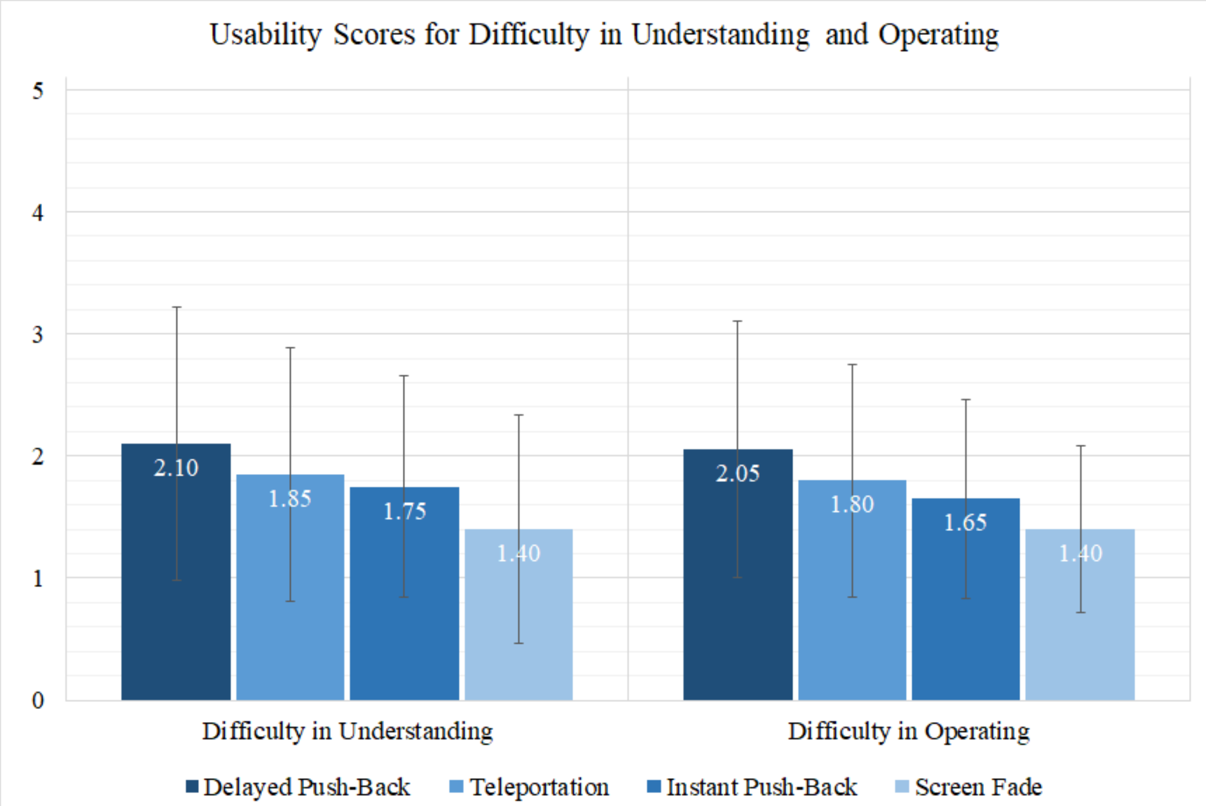

Figure 4.4: The usability scores for difficulty in understanding and operating the method.

4.3.2 Required Effort and Tiredness

The usability scores for required effort and tiredness while using the method were analyzed using Friedman tests due to non-normality. The method of handling collisions did not significantly influence the scores for required effort ($\chi^2(3) = 5.057$, $p = 0.168$). However, the tests revealed that the scores for tiredness were significantly influenced by the method ($\chi^2(3) = 11.231$, $p = 0.011$). Post-hoc Wilcoxon signed-rank tests revealed that the screen fade method led to significantly lower scores for tiredness than the delayed push-back method ($p = 0.007$). See Figure 4.5 for an overview of the usability scores for required effort and tiredness while using the method.

4.3.3 Feeling of Being in Control and Enjoyment

The usability scores for the feeling of being in control and enjoyment while using the method were analyzed using Friedman tests due to non-normality. The method of handling collisions significantly influenced the scores for the feeling of being in control ($\chi^2(3) = 5.057$. Post-hoc Wilcoxon Signed Rank tests revealed that the instant push-back method led to significantly higher scores for the feeling of being in control than the delayed push-back method ($p = 0.002$). The Friedman tests also revealed that the scores for enjoyment were significantly influenced by the method ($\chi^2(3) = 16.297$, $p < 0.001$). Post-hoc Wilcoxon signed-rank tests revealed that the screen fade method led to significantly higher scores for enjoyment than the delayed push-back ($p = 0.003$) and teleportation ($p = 0.004$). See Figure 4.6 for an overview of the usability scores for the feeling of being in control and enjoyment while using the method.

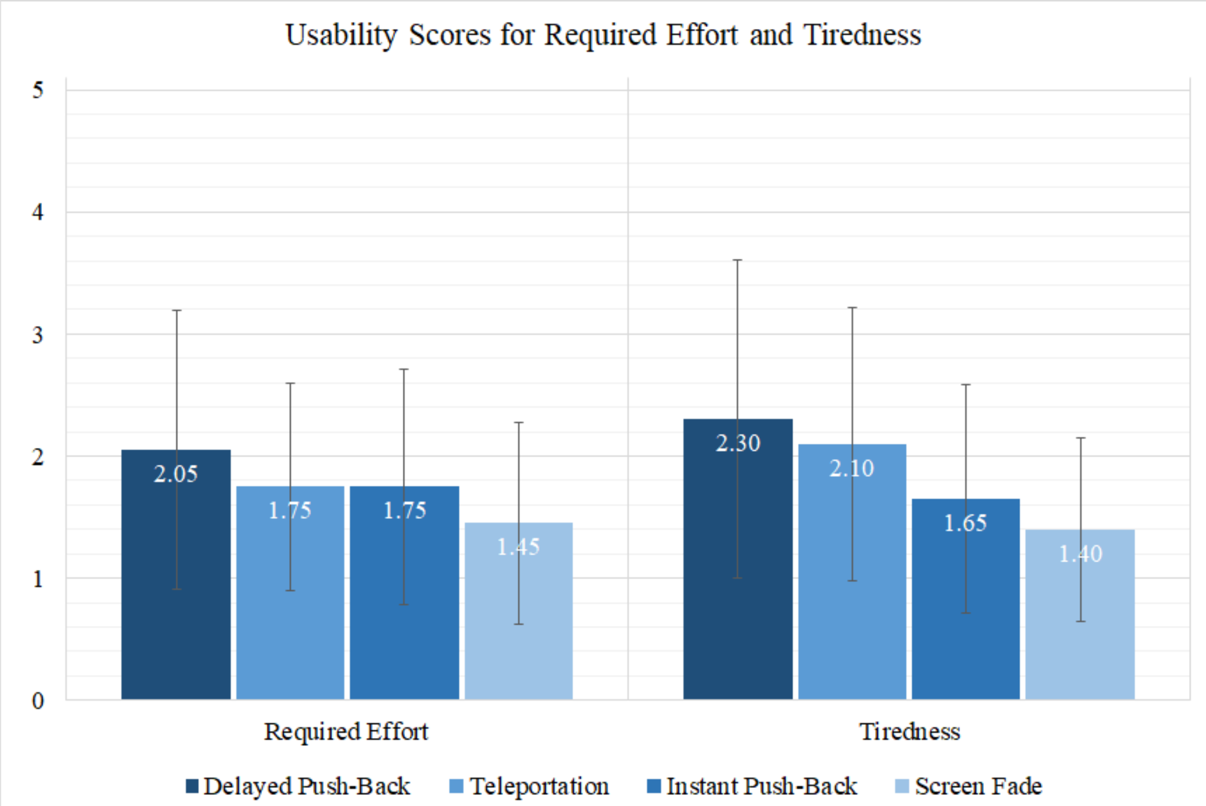

Figure 4.5: The usability scores for required effort and tiredness while using the method.

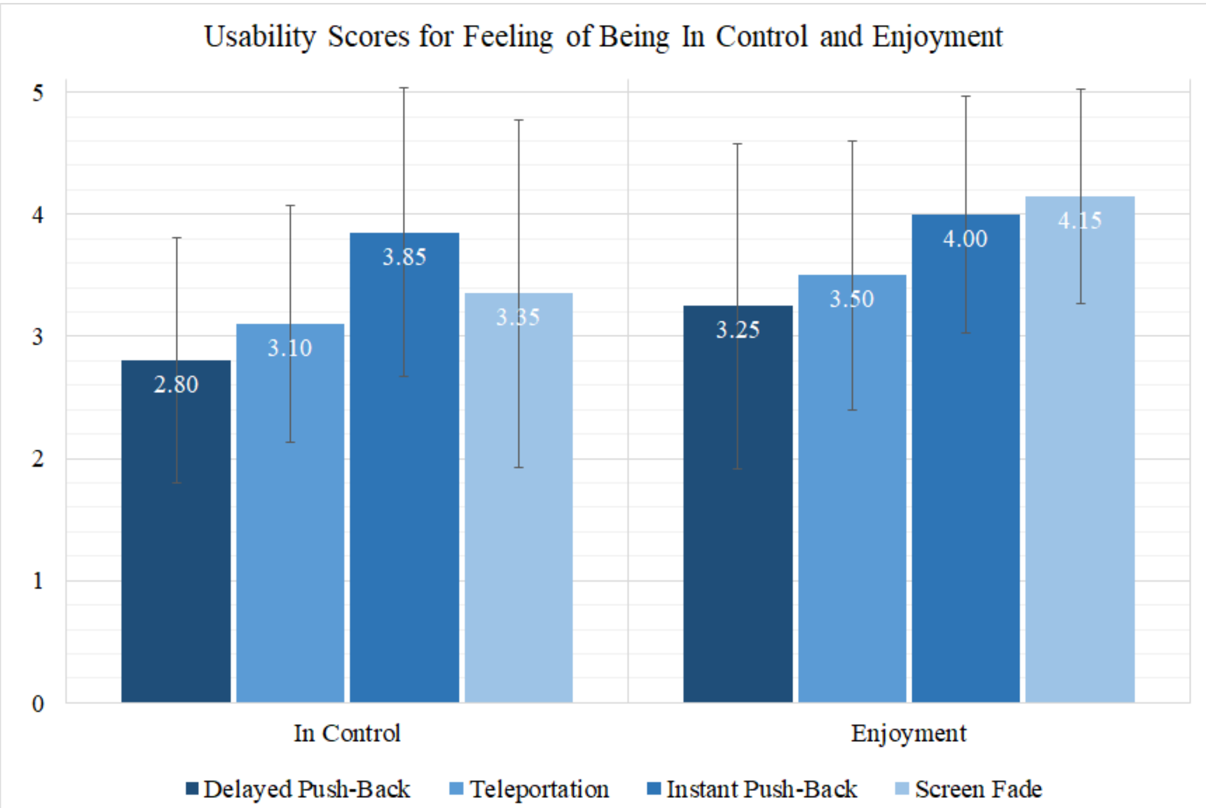

Figure 4.6: The usability scores for the feeling of being in control and enjoyment while using the method.

4.3.4 Feeling of Being Overwhelmed and Frustration

The usability scores for the feeling of being overwhelmed and frustration while using the method were analyzed using Friedman tests due to non-normality. The method of handling collisions did not significantly influence the scores for the feeling of being overwhelmed ($\chi^2(3) = 3.675$, $p = 0.299$). However, the tests revealed that the scores for frustration were significantly influenced by the method ($\chi^2(3) = 13.227$, $p = 0.004$). Post-hoc Wilcoxon signed-rank tests revealed that the screen fade method led to significantly lower scores for frustration than the delayed push-back method ($p = 0.004$). See Figure 4.7 for an overview of the usability scores for the feeling of being overwhelmed and frustration while using the method.

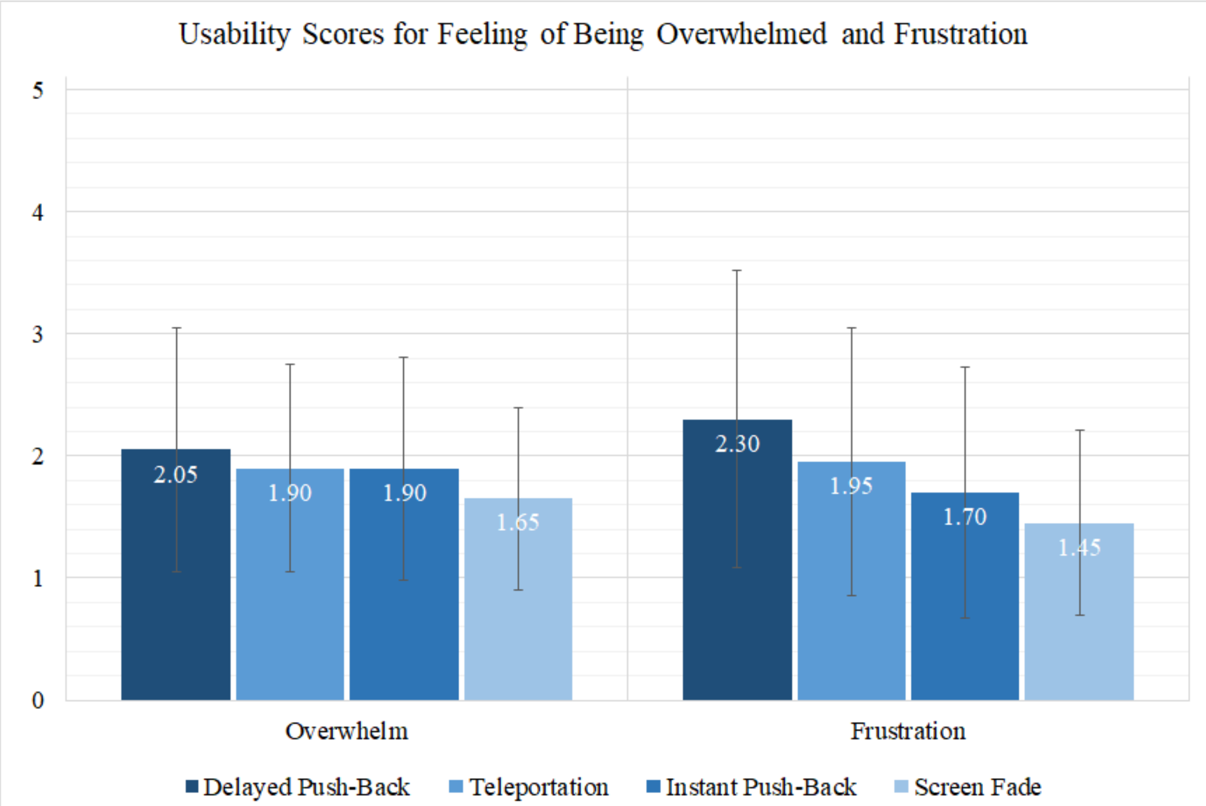

Figure 4.7: The usability scores for the feeling of being overwhelmed and frustration while using the method.

4.3.5 Total Usability Scores

The total usability scores were calculated and were analyzed using a repeated measures ANOVA. Shapiro-Wilk tests indicated that the assumption of normality was not violated; and Mauchly's test indicated that the assumption of sphericity was met ($\chi^2(3) = 8.08$, $p = 0.152$). The repeated measures ANOVA revealed that the total usability scores were significantly influenced by the method of handling collisions ($F(3, 76) = 8.887$, $p < 0.0001$). Post-hoc pairwise comparisons revealed higher usability scores for the screen fade method compared to the delayed push-back ($p = 0.005$) and teleportation ($p = 0.021$). The comparisons also revealed higher usability scores for the instant push-back method compared to the delayed push-back method ($p = 0.03$). See Figure 4.8 for an overview of the total usability scores.

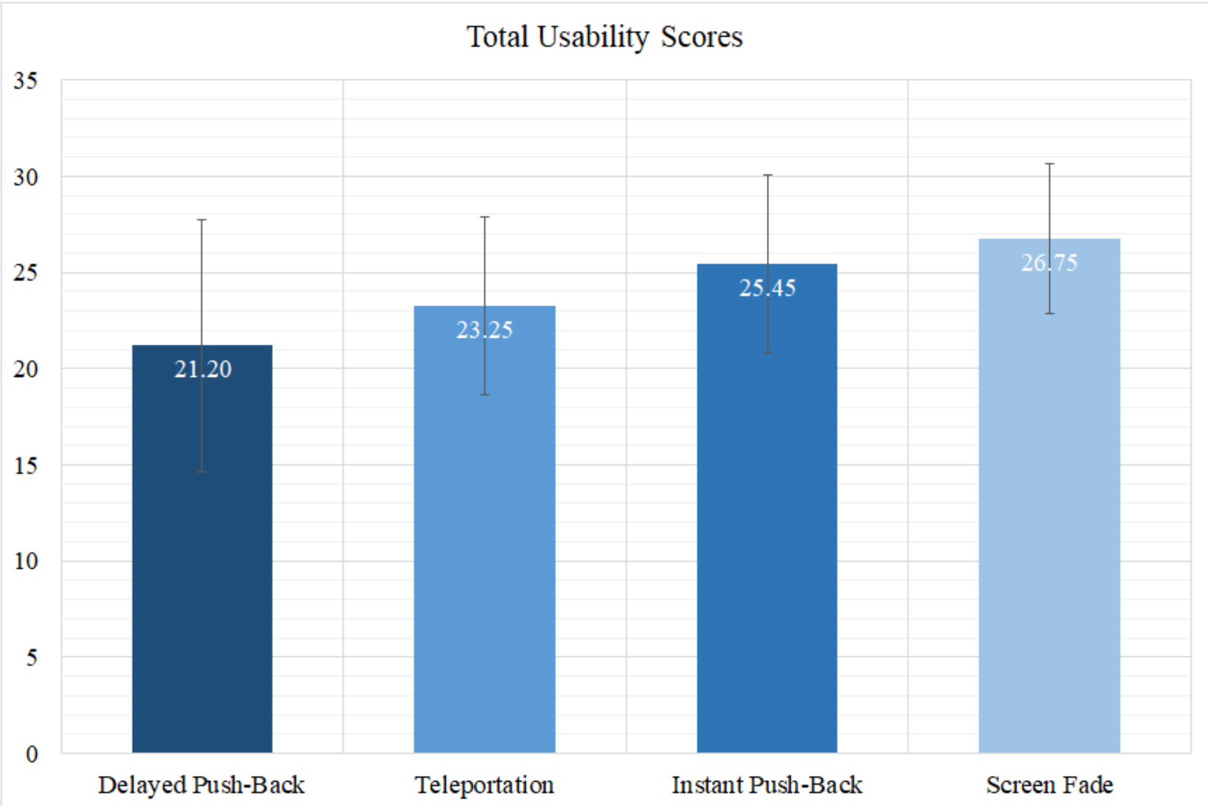

Figure 4.8: The total usability scores.

Chapter 5

Discussion

5.1 VR Sickness

The first research question in this study sought to determine how the proposed solutions to the problem of VR head collisions affect virtual reality sickness. The results support the hypothesis that some solutions have more positive effect than others. Both disorientation and total SSQ scores were significantly lower for the screen fade method than the delayed push-back method. No differences were found between any other of the four methods. There were also no significant differences revealed in the case of SSQ nausea and oculumotor scores. However, the SSQ disorientation scores were much higher than the oculomotor and nausea scores, which further support the idea that VR sickness tends to be characterized by the disorientation disturbances.

The high scores of the delayed push-back method explain the complaints that can be found in many internet forums. This method was chosen by some VR developers and the players reported that it had great impact on virtual reality sickness. The most likely reason for the high scores is that this method for a brief moment takes control of camera movements away from the player. It is proven that any unexpected accelerations and movements of the camera not initiated by the player's physical movement are some of the main causes of VR sickness. In this study, the method was implemented in the way that allowed the player to move his head during the duration of the push-back effect as opposed to completely disabling the head tracking. The SSQ scores would most likely be even higher if the method was implemented in a different way.

In contrast to earlier findings, no evidence of difference between the screen fade method and the instant push-back was detected. The previous research found that the instant push-back achieved higher SSQ scores than the screen fade method [51]. Possible explanations for these results may be the longer duration of the experiment, different experiment design, or slightly different implementations of the methods. The symptoms of VR sickness tend to increase the longer the VR experience lasts. In the previous research, the participants tested different solutions for 10 minutes by playing a simple game in virtual environment with narrow corridors.

5.2 Sense of Presence

The second research question sought to find how the studied methods affect the sense of presence. The results again support the hypothesis that some methods have more positive effect than others. The screen fade method leads to a significantly higher sense of presence than the teleportation and delayed push-back methods. Moreover, the instant push-back method provides a significantly higher sense of presence than the delayed push-back method. However, no significant difference was found between the screen fade method and the instant push-back method.

There are several possible explanations for these results. During testing the screen fade method, the participants often commented that fading the screen to black feels the most natural to them. Some participants explained that this effect resembles the darkness due to closing the eyes when their heads collide with objects in the real world. During testing the instant push-back method, some participants commented that they felt like they are pushing themselves away from the object by using their heads, which again in some way resembles how their feet would be pushed backwards on a slippery floor in the real world. Moreover, the screen fade and instant push-back methods are the only techniques where the players are never able to see the insides of objects and unexpected clipping artifacts. In the delayed push-back and teleportation methods, the players are able to see the insides of objects for a brief moment before the methods start to work and relocate them to a new position.

5.3 Usability

The third and final research question in this study sought to identify how usable are the proposed solutions. The results back the hypothesis that some solutions have higher level of usability than others. The exact same situation as in the sense of presence case repeated for total usability scores: the screen fade method leads to a significantly higher level of usability than the teleportation and delayed push-back methods, and the instant push-back method provides a significantly higher level of usability than the delayed push-back method. Once again, no significant difference was found between the screen fade method and the instant push-back method.

The participants of the experiment were not told how the methods work and had to discover it on their own. However, they had no trouble in operating the methods and quickly understood how they function. No significant differences were found between the methods in this case. This result may be explained by the fact that each method is triggered in a similar way. Some of the participants were slightly confused at first when they tested the teleportation and delayed push-back methods. In these cases, the methods do not work instantly after colliding with the headset, but after a second of constant collision. However, after a brief investigation the participants were able to trigger the effect and had no trouble finishing the experiment with the remaining objects.

Although there were no significant differences found in the required effort scores, the scores for tiredness were significantly influenced by the method of handling collisions. This rather contradictory result may be due to the effects of VR sickness. The results for tiredness mirror these found in VR sickness section: the screen fade method achieved significantly lower scores than the delayed push-back method. While the participants felt like the methods are equally demanding, the higher tiredness scores may be attributed to the increases in VR sickness symptoms.

The results show that the participants felt more in control while they tested the instant push-back method compared to the delayed push-back method. This result may be explained by the fact that the users lose some control of the movement for a longer duration in the delayed push-back method. In the instant push-back method, the users manually initiate the effect by pushing their heads forward in the direction of the collision and can stop doing it at any time. The vision is also never obscured for a brief moment like in the teleportation and screen fade methods and the users can see what is happening on the screen all the time.

Another important finding is that the screen fade method is more enjoyable than the delayed push-back and teleportation methods. Furthermore, the results indicate that the delayed push-back method is more frustrating to experience than the screen fade method. There are a couple of possible explanations for these results. During testing the screen fade method, some participants liked the visual effect of gradual fading. They repeated moving the head in and out of the object, even if its color was already changed to green. Although the participants mostly enjoyed discovering how the teleportation and delayed push-back methods work, after experiencing them for the first time, some participants found it frustrating to wait a full second to trigger the effect with the remaining objects.

Chapter 6

Conclusions

In this study, four different solutions to the problem of VR head collisions were described and evaluated. The screen fade, delayed push-back, instant push-back, and teleportation methods were implemented and then tested in a specially designed virtual environment. 20 participants were recruited and completed the experiment, in which they had to collide with 10 various objects while using one of the solution to the problem. After testing each method, they filled in post-test questionnaires that measured what effects these solutions have on many different factors. The questionnaires results were analyzed using statistical tests and interpreted to determine which solution should be used in future VR applications. All objectives of the study were fulfilled and the results confirmed that some solutions to the problem of VR head collisions have more positive effect than others on VR sickness, the sense of presence, and the usability level.

Overall, the screen fade method turned out to be the most efficient one of the four solutions and should be the first choice for VR developers. It is characterized by a simple implementation that can be easily integrated into any VR application. It has more positive effect than the delayed push-back method in terms of VR sickness, sense of presence, tiredness, enjoyment, frustration, and general usability. It also achieves better scores than the teleportation method in terms of usability, enjoyment, and sense of presence. The instant push-back method had mostly neutral results. It only has more positive effect than the delayed push-back method in terms of usability, feelings of control, and sense of presence. No significant differences were found between the delayed push-back and the screen fade method. It is recommended to use this solution in place of the screen fade method if the developer does not want to obstruct the vision of the players at any time. The teleportation method also had neutral scores for VR sickness. However, it achieved substandard scores for the sense of presence and usability, and it generally should not be the preferred solution. The delayed push-back method ranked the worst in all categories and should be avoided by VR developers.

Although the study has successfully demonstrated that some solutions have more positive effects than others on many different factors, the research was limited in several ways. The obtained results are based on specific, most commonly used implementation of the methods. Slight modifications to these solutions may completely change how they are perceived by the users. Furthermore, due to time constraints, only four different solutions to the problem of VR head collisions were examined. There are many more techniques that can be implemented and compared with the solutions described in this study. Another limitation is that the number of participants that completed the experiment was relatively small, and the duration of tests for each method lasted only a couple of minutes. The symptoms of VR sickness tend to increase the longer the VR experience lasts, which can affect the experiment results. In the future, it is advised to conduct similar experiments with a larger pool of participants and with longer duration of tests if VR sickness is the main focus.

The screen fade method turned out to be the best in terms of many factors, however, this solution still has one minor issue that sometimes occurs in teleportation locomotion techniques. The users can unintentionally teleport to some head-object colliding position, and then be stuck with obscured screen without knowing in what direction they should move to escape the darkness. Further research in this field might explore the ways how to prevent this situation. For example, some visual cues that guide the users might help them move out of the collisions. In the case of other promising solutions to the problem of VR head collisions, a future study investigating the object fade method is strongly recommended. Object fade is a technique in which, rather than fading the whole screen to black, only parts of the colliding objects fade out as the camera gets closer to them. Due to the similarity to the screen fade method and the possibility to add some interesting fading visual effects, this solution seems now the most promising.

Bibliography

[1] A. Aguirre. Human-joystick vr locomotion tecnique: An empirical approach. Master's thesis, Norwegian University of Science and Technology, 2018.

[2] E. Amos. Sony PlayStation 4 PSVR Headset image. `https://commons.wikimedia.org/wiki/File:Sony-PlayStation-4-PSVR-Headset-Mk1-FL.jpg`. Accessed: 2019-01-07.

[3] E. Amos. The Oculus Rift CV1 Headset image. `https://commons.wikimedia.org/wiki/File:Oculus-Rift-CV1-Headset-Front.jpg`. Accessed: 2019-01-07.

[4] C. Anthes, R. J. García-Hernández, M. Wiedemann, and D. Kranzlmüller. State of the art of virtual reality technology. *2016 IEEE Aerospace Conference*, pages 1–19, 2016.

[5] Bethesda Forums. Skyrim PlayStation VR Bug: Teleport through walls & doors. `https://bethesda.net/community/category/216/skyrim-playstation-vr`. Accessed: 2019-01-07.

[6] C. Boletsis. The new era of virtual reality locomotion: A systematic literature review of techniques and a proposed typology. *Multimodal Technologies and Interaction*, 1:24, 2017.

[7] C. Boletsis, J. E. Cedergren, and S. Kongsvik. HCI Research in Virtual Reality: A Discussion of Problem-solving. *In Proceedings of the 11th International Conference on Interfaces and Human Computer Interaction*, pages 263–267, 2017.

[8] E. Bozgeyikli, A. Raij, S. Katkoori, and R. Dubey. Point & teleport locomotion technique for virtual reality. *Proceedings of the 2016 Annual Symposium on Computer-Human Interaction in Play*, pages 205–216, 2016.

[9] J. Diaz. Google Working On VR Shoes That Let You Walk Forever In Your Living Room. `https://www.tomsguide.com/us/google-vr-shoes-patent,news-28546.html`. Accessed: 2019-01-07.

[10] EleVR. Collision in VR: 9 Techniques. `http://elevr.com/collision-in-vr/`. Accessed: 2019-01-07.

[11] A. S. Fernandes and S. K. Feiner. Combating vr sickness through subtle dynamic field-of-view modification. *2016 IEEE Symposium on 3D User Interfaces (3DUI)*, page 201–210, 2016.

[12] J. Frommel, S. Sonntag, and M. Weber. Effects of controller-based locomotion on player experience in a virtual reality exploration game. *Proceedings of the 12th International Conference on the Foundations of Digital Games*, 2017.

[13] Github. SteamVR Unity Plugin. https://github.com/ValveSoftware/steamvr_unity_plugin. Accessed: 2019-01-07.

[14] J. Habgoodand, D. Moore, D. Wilson, and S. Alapont. Rapid, continuous movement between nodes as an accessible virtual reality locomotion technique. *2018 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, pages 371–378, 2018.

[15] T. Heath. Research into Comfortable Locomotion. https://developer.oculus.com/blog/research-into-comfortable-locomotion/. Accessed: 2019-01-07.

[16] M. L. Heilig. Stereoscopic-television apparatus for individual use. https://patents.google.com/patent/US2955156A/en. Accessed: 2019-01-07.

[17] HTC Vive Controller. https://www.vive.com/us/accessory/controller/. Accessed: 2019-01-07.

[18] HTC Vive Virtual Reality System. https://www.vive.com/us/product/vive-virtual-reality-system/. Accessed: 2019-01-07.

[19] C. Hunt. These VR games do teleportation the right way. https://www.windowscentral.com/these-vr-games-do-teleportation-right-way/. Accessed: 2019-01-07.

[20] A. Kemeny, P. George, F. Merienne, and F. Colombet. New vr navigation techniques to reduce cybersickness. *The Engineering Reality of Virtual Reality*, pages 48–53, 2017.

[21] R. S. Kennedy, N. E. Lane, K. Berbaum, and M. G. Lilienthal. Simulator sickness questionnaire: An enhanced method for quantifying simulator sickness. *The International Journal of Aviation Psychology*, 3:203–220, 1993.

[22] Kickstarter. Gloveone: Feel Virtual Reality. https://www.kickstarter.com/projects/gloveone/gloveone-feel-virtual-reality. Accessed: 2019-01-07.

[23] E. M. Kolasinski. *Simulator Sickness in Virtual Environments*. U.S. Army Research Institute for the Behavioral and Social Sciences, 1995.

[24] A. Kurvet. Sample screen capture of Oculus rift development kit 2 screen buffer. https://commons.wikimedia.org/wiki/File:Sample_screen_capture_of_Oculus_rift_development_kit_2_screen_buffer.jpg. Accessed: 2019-01-07.

[25] E. Langbehn, P. Lubos, and F. Steinicke. Evaluation of locomotion techniques for room-scale vr: Joystick, teleportation, and redirected walking. *Proceedings of the Virtual Reality International Conference*, 2018.

[26] S. M. LaValle. *Virtual Reality*. Cambridge University Press, 2019.

[27] J. J. LaViola. A discussion of cybersickness in virtual environments. *ACM SIGCHI Bulletin*, 32:47–56, 2000.

[28] Leap Motion. Developer Documentation. https://developer.leapmotion.com/documentation/. Accessed: 2019-01-07.

[29] P. Lopes, S. You, L. Cheng, S. Marwecki, and P. Baudisch. Providing Haptics to Walls & Heavy Objects in Virtual Reality by Means of Electrical Muscle Stimulation. *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*, pages 1471–1482, 2017.

[30] MathWorks. Matlab. https://www.mathworks.com/products/matlab.html. Accessed: 2019-01-07.

[31] Oculus Documentation. VR Best Practices: Locomotion. https://developer.oculus.com/design/latest/concepts/bp-locomotion/. Accessed: 2019-01-07.

[32] Oculus Support Forums. Handling head clipping. https://forums.oculusvr.com/developer/discussion/6312/handling-head-clipping. Accessed: 2019-01-07.

[33] L. Rebenitsch and C. B. Owen. Review on cybersickness in applications and visual displays. *Virtual Reality*, 20:101–125, 2016.

[34] Reddit. R/oculus - Rant: Player pushback is the absolute worst method to tackle "VR cheating" (head inside an object). https://www.reddit.com/r/oculus/comments/975rv1/rant_player_pushback_is_the_absolute_worst_method/. Accessed: 2019-01-07.

[35] Reddit. R/skyrimvr - Is it possible to avoid the push-back from players/walls without changing bAllowVRCheating? https://www.reddit.com/r/skyrimvr/comments/8n533f/is_it_possible_to_avoid_the_pushback_from/. Accessed: 2019-01-07.

[36] Reddit. R/unity3D - Using a screen fade in VR to avoid people seeing through walls or peeking behind closed doors. https://www.reddit.com/r/Unity3D/comments/80wu7i/using_a_screen_fade_in_vr_to_avoid_people_seeing/. Accessed: 2019-01-07.

[37] Reddit. R/Vive - Fallout 4 VR Thoughts + Locomotion issues. https://www.reddit.com/r/Vive/comments/7j9tgx/fallout_4_vr_thoughts_locomotion_issues/. Accessed: 2019-01-07.

[38] V. Schwind, P. Knierim, N. Haas, and N. Henze. Using presence questionnaires in virtual reality. *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*, 2019.

[39] K. M. Stanney, R. S. Kennedy, and J. M. Drexler. Cybersickness is not simulator sickness. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, 41(2):1138–1142, 1997.

[40] I. E. Sutherland. A head-mounted three dimensional display. *Fall Joint Computer Conference*, pages 757–764, 1968.

[41] G. Szauer. Teleport Curves with the Gear VR Controller. https://developer.oculus.com/blog/teleport-curves-with-the-gear-vr-controller/. Accessed: 2019-01-07.

[42] Unity Asset Store. Wand and Circles. Polygon City Pack - Environment and Interior [Free]. https://assetstore.unity.com/packages/3d/polygon-city-pack-environment-and-interior-free-101685. Accessed: 2019-01-07.

[43] Unity Documentation. Sphere Collider. `https://docs.unity3d.com/Manual/class-SphereCollider.html`. Accessed: 2019-01-07.

[44] Unity Technologies. The Unity Game Engine. `https://unity3d.com/unity`. Accessed: 2019-01-07.

[45] M. Usoh, E. Catena, S. Arman, and M. Slater. Using presence questionnaires in reality. *Presence: Teleoperators and Virtual Environments*, 9:497–503, 2000.

[46] VRTK - Virtual Reality Toolkit. `https://www.vrtk.io/`. Accessed: 2019-01-07.

[47] VRTK Documentation. VRTK_HeightAdjustTeleport. `https://vrtoolkit.readme.io/docs/vrtk_heightadjustteleport`. Accessed: 2019-01-07.

[48] VRTK Documentation. VRTK_PositionRewind. `https://vrtoolkit.readme.io/docs/vrtk_positionrewind`. Accessed: 2019-01-07.

[49] Wikipedia Commons. The Sensorama image. `https://commons.wikimedia.org/wiki/File:Sensorama-morton-heilig-virtual-reality-headset.jpg`. Accessed: 2019-01-07.

[50] Youtube. Don't just teleport - How to walk around something that is bigger than your tracked space. `https://www.youtube.com/watch?v=At_Zac4Xezw`. Accessed: 2019-01-07.

[51] P. Ziegler, D. Roth, A. Knots, M. Kreuzer, and S. Mammen. Simulator sick but still immersed: A comparison of head-object collision handling and their impact on fun, immersion, and simulator sickness. *Proceedings of the 2018 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, pages 743–744, 2018.

List of Figures

Appendix A

Demographic Questionnaire

1. **Age**

   ____

2. **Gender**

   Mark only one oval.

   - ◯ Female
   - ◯ Male
   - ◯ Prefer not to say
   - ◯ Other: ____________________

3. **How much VR experience do you have?**

   Mark only one oval.

   - ◯ I have never used a VR headset before.
   - ◯ I have used a VR headset once.
   - ◯ I have used a VR headset a couple of tmes.
   - ◯ I have used a VR headset multiple times.
   - ◯ Other: ____________________

4. **Have you ever experienced motion sickness?**

   Mark only one oval.

   - ◯ Yes
   - ◯ No
   - ◯ Other: ____________________

Appendix B

Post-Test Questionnaire

1. **Tested method:**

   Mark only one oval.

   - Screen fade
   - Teleportation
   - Instant push-back
   - Delayed push-back

2. **How much each symptom below is affecting you right now?**

   Mark only one oval per row.

	None	Slight	Moderate	Severe
General discomfort				
Fatigue				
Headache				
Eye strain				
Difficulty focusing				
Salivation increasing				
Sweating				
Nausea				
Difficulty concentrating				
"Fullness of the Head"				
Blurred vision				
Dizziness with eyes open				
Dizziness with eyes closed				
Vertigo				
Stomach awareness				
Burping				

3. **Please rate your sense of being in the virtual environment, on the following scale from 1 to 7, where 7 represents your normal experience of being in a place.**

   Mark only one oval.

	1	2	3	4	5	6	7	
Not at all								Very much

4. **To what extent were there times during the experience when the virtual environment was the reality for you?**
Mark only one oval.

	1	2	3	4	5	6	7	
At no time								Almost all the time

5. **When you think back to the experience, do you think of the virtual environment more as images that you saw or more as somewhere that you visited?**
Mark only one oval.

	1	2	3	4	5	6	7	
Images that I saw								Somewhere that I visited

6. **During the time of the experience, which was the strongest on the whole, your sense of being in the virtual environment or of being elsewhere?**
Mark only one oval.

	1	2	3	4	5	6	7	
Being elsewhere								Being in the virtual environment

7. **Consider your memory of being in the virtual environment. How similar in terms of the structure of the memory is this to the structure of the memory of other places you have been today? By 'structure of the memory' consider things like the extent to which you have a visual memory of the virtual environment, whether that memory is in colour, the extent to which the memory seems vivid or realistic, its size, location in your imagination, the extent to which it is panoramic in your imagination, and other such structural elements.**
Mark only one oval.

	1	2	3	4	5	6	7	
Not at all								Very much so

8. **During the time of your experience, did you often think to yourself that you were actually in the virtual environment?**

Mark only one oval.

	1	2	3	4	5	6	7	
Not very often								Very much so

9. **Rate the tested method with the following usability factors. Use the scale from 1 to 5, where 1 represents "not at all" and 5 respresents "very much".**

Mark only one oval per row.

	1	2	3	4	5
Difficulty in understanding the method					
Difficulty in operating the method					
Feeling of being in control while using the method					
Required effort to use the method					
Feeling of tiredness while using the method					
Feeling of enjoyment while using the method					
Feeling of being overwhelmed while using the method					
Feeling of frustration while using the method					