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Effects of Locomotion Methods on Game Design in Virtual Reality

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Tiivistelmä — Referat — Abstract

In recent years, virtual reality devices have entered the mainstream with many gaming-oriented consumer devices. However, the locomotion methods utilized in virtual reality games are yet to gain a standardized form, and different types of games have different requirements for locomotion to optimize player experience. In this thesis, we compare some popular and some uncommon locomotion methods in different game scenarios. We consider their strengths and weaknesses in these scenarios from a game design perspective. We also create suggestions on which kind of locomotion methods would be optimal for different game types. We conducted an experiment with ten participants, seven locomotion methods and five virtual environments to gauge how the locomotion methods compare against each other, utilizing game scenarios requiring timing and precision. Our experiment, while small in scope, produced results we could use to construct useful guidelines for selecting locomotion methods for a virtual reality game. We found that the arm swinger was a favourite for situations where precision and timing was required. Touchpad locomotion was also considered one of the best for its intuitiveness and ease of use. Teleportation is a safe choice for games not requiring a strong feeling of presence.

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1 Introduction

In recent years, virtual reality headsets (HMDs, Head-mounted Displays) and controllers with positional and rotational tracking capabilities have entered the mainstream. These binocular devices utilize outside-in tracking methods such as the base stations of the Valve Index or inside-out tracking methods such as the cameras of the Oculus Rift S to allow the user to move in and interact with a virtual environment. Platforms such as SteamVR, OpenXR, and the Oculus Platform provide easy-to-use interfaces for software development for these devices [1, 2, 3]. The lowered barrier of entry into VR software development has led to a massive influx of virtual reality games, experiences, and other applications [4].

Locomotion in virtual reality, however, is still in flux. Some games choose to utilize one locomotion method, while others try to support many to be inclusive towards people's personal needs. The selection of supported locomotion options is a crucial choice for a virtual reality game. Different people are comfortable with different locomotion methods, with others causing unease or physical symptoms such as motion sickness [5, 6]. To make a game appealing and usable to a broad audience, developers aim to implement as many locomotion methods as possible.

Games strive to be as engaging as possible to their players, to make them have fun. This increases player retention, the players' willingness to return to the game again and again. To this end, a metric called player experience (PX) can be utilized [7]. In virtual reality, immersive, easy, comfortable and fun locomotion is a key aspect of player experience. Locomotion methods that are difficult to use or cause motion sickness decrease the players' willingness to play the game.

However, different game environments behave very differently based on the used locomotion method, which affects the game's design; for example, teleportation-based locomotion behaves very differently to walk-in-place locomotion when crossing wide gaps in a virtual terrain, because the former trivializes the challenge of crossing the gap. The virtual reality platform might also cause limitations because of its input methods, or it might implement some unique feature that provides a novel tool for some locomotion method.

Immersion is also a key feature of virtual reality, and some locomotion methods interact with the real world in a way that prohibits the user from being fully immersed in the virtual world [8, 9, 10]. For example, teleportation is not something that happens in the real world; the nature of the locomotion method itself clearly separates it from real-world locomotion. In addition, the teleportation locomotion method does not simulate movement per se; it merely provides the user with a convenient means of transportation from spot to spot. This lack of actual movement hinders it from being exciting in gameplay situations where more classic movement replicates reality better, such as when an enemy chases the player.

In this thesis, we examine some common and some experimental locomotion methods used in PC-based virtual reality games and applications. We analyze the effects and restrictions these methods have on game design in these games. Using these locomotion methods, we consider different environmental situations that might arise in a virtual reality game and research which locomotion methods are most suitable for each environmental setup. We also consider the locomotion methods' intuitiveness to the user, subjective immersion, and suitability to highly varying environments. We conduct an experiment in a virtual reality environment utilizing these locomotion methods in different combinations on an HTC Vive setup and collect results from participants with a survey. The virtual reality setup is shown in Figure 1.1. Finally, we conclude how intuitive, immersive, and multi-functional the tested locomotion methods are for different environmental situations based on the survey results. From these conclusions, we construct suggestions on locomotion method combinations suitable for different kinds of games. We also propose game design considerations that improve the locomotion experience.

Figure 1.1: The HTC Vive virtual reality set used in this work [11]. The set contains a head-mounted display (HMD), two base stations and two wand controllers.

First, we will explore the background of locomotion within virtual reality environments, and present different ways to categorize them. After this, we briefly examine game design principles for first-person character controllers in virtual reality. In the next chapter, we present the locomotion methods and virtual reality environments used in the experiment, and explain how the experiment was run. After this, we present the results and examine them in depth for each locomotion method and each environment. Finally, we discuss these results and make conclusions based on them.

2 Background

This chapter discusses what locomotion in virtual reality is, how games and other virtual reality applications usually handle it, and how to categorize different locomotion methods. We also briefly go through the previous research done on the subject.

2.1 State of the art in locomotion in virtual reality

Birk and Mandryk researched how the controller type affects the player's enjoyment of a game [7]. In this thesis, we utilize some of their ideas on player enjoyment and apply them to virtual reality locomotion.

Some previous research exists in the evaluation of different locomotion methods for virtual reality. Little focus, however, is placed on the effect the available locomotion methods have on game design. Frommel, Sonntag, and Weber researched some locomotion methods, teleportation, and touchpad based movement, in their paper, and concluded that for player experience, teleportation is the best method [12]. In this thesis, we examine the locomotion methods with a wider variety of evaluation criteria, also taking into account ease of use and how the users felt about different gameplay situations.

Boletsis and Cedergren conducted a similar experiment to ours [13], but with less different locomotion methods. We will discuss how our results compare to theirs in the discussion chapter.

Much research on virtual reality locomotion has also been done using specialized hardware, such as treadmills, eye-tracking or additional external trackers [14, 15]. However, while many commercially available but expensive virtual reality treadmills exist, in this thesis we focus on locomotion methods utilizing only technology found in the most popular mass-market virtual reality systems, because they form the current standard hardware baseline for virtual reality games.

2.2 Locomotion in virtual reality

The word *locomotion* refers to the act of movement or transportation from one location to another [16]. In virtual reality, applications utilize locomotion, user-initiated or not, to expand the environment beyond the user's immediate vicinity and the space's physical limits.

In the early modern virtual reality headsets of the 2010s, such as the Oculus Rift, the tracking for the user's headset allows for little movement within the virtual reality environment, and the user is mostly stationary in the physical space. All locomotion has to be implemented artificially, such as with the joystick of a gamepad. Later headsets, such as the HTC Vive, allow the user to move in *room-scale* by tracking the headset's position and rotation inside specified bounds.

The virtual reality device can implement tracking with base stations, infrared-emitting devices that form a grid that the sensors on the headset can detect, or with inside-out tracking, utilizing cameras of the headset itself. The outside-in base station method is utilized by headsets such as HTC Vive and Valve Index, whereas many Windows Mixed Reality headsets and the newer Oculus headsets such as the Quest and the Rift S use the inside-out method.

2.3 History of virtual reality

The term *virtual reality* was popularized by Jaron Lanier in the 80s [17]. The idea of virtual reality had long been a subject of science fiction but was becoming more realistic to implement as displays decreased in size and weight. Many papers were written on the subject, imagining for example conference spaces in virtual reality, as seen in Figure 2.1 [18]. An example of an early consumer-oriented virtual reality device is the Nintendo Virtual Boy from 1995, which utilized a monochrome red led display within the HMD to simulate depth.

The popularization of virtual reality devices resurged in 2012 when Oculus (later acquired by Facebook) launched the Oculus Rift crowd-funding campaign on Kickstarter [19]. After this, multiple other companies such as Samsung, Google, and Valve also began creating their own virtual reality systems and standards. Nowadays, OpenXR represents an open standard for virtual and augmented reality systems [2].

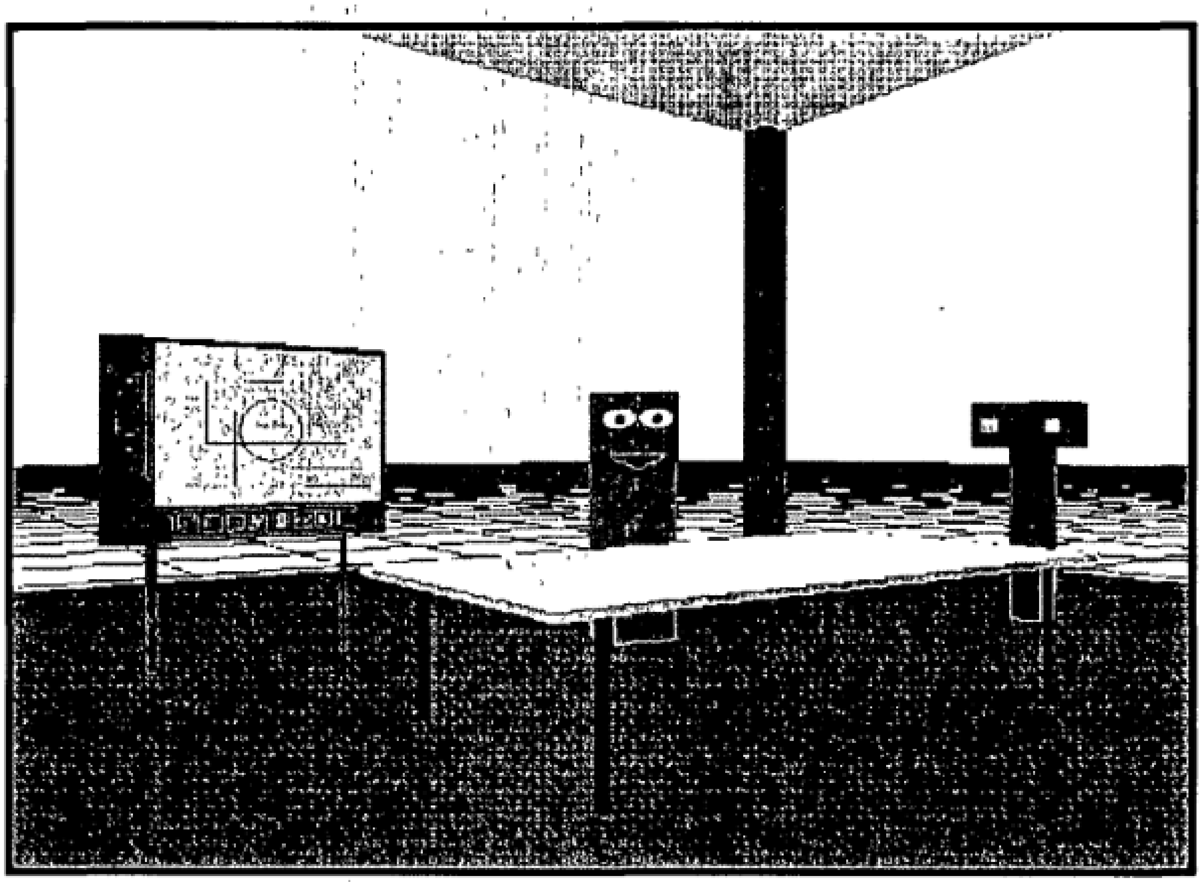

Figure 2.1: Representation of a virtual reality environment in the 1993 paper *A Spatial Model of Interaction in Large Virtual Environments* by Benford and Fahlén. [18].

In September 2020, the Steam Hardware & Software Survey lists Oculus Rift S as the most popular headset, followed by HTC Vive and Valve Index [20].

2.4 Categorization of locomotion methods

In the paper *The New Era of Virtual Reality Locomotion: A Systematic Literature Review of Techniques and a Proposed Typology* Boletsis conducts an extensive literature review of different locomotion methods and proposes methods to classify them [9]. In this thesis, we categorize locomotion methods utilizing some of those classifications. A useful way to divide locomotion methods by their interaction type is the split of physical and artificial locomotion methods. Furthermore, locomotion methods can also be classified as having a continuous or non-continuous motion type. These are explained in more detail in the following subsections.

2.4.1 Physical methods

In physical locomotion methods, the user needs to do some physical activity to move, and this act corresponds to the way the user moves – for example, room-scale locomotion is initiated by the user moving the headset physically within the area's bounds [9]. Physical locomotion methods can also involve the user doing some activity, such as swinging their arms, with the motion-tracking controllers.

Motion-based methods aim to mimic real-world movement. These methods aim to be immersive, as the user input of physical movement is directly transformed into in-game movement. These methods include the arm swinger locomotion, walk-in-place locomotion and locomotion based on walking in the room-scale space [21, 22].

Room-scale movement means the act of the player physically moving around some pre-configured confined bounds, and likewise, their virtual avatar moving in the virtual environment in the same way, usually on a 1:1 scale. Room-scale is the locomotion method that most closely represents locomotion in the real world, but has the disadvantage of being confined to a limited area. Inside-out tracking methods, with multiple cameras on the headset, allow the tracked area to be larger than the hard limits set by base stations, but as virtual reality systems are generally used indoors, there are still physical, real-world limitations to where the user can move because of walls and furniture. For these reasons, room-scale based movement is typically paired with some other locomotion method; this allows the user to move with room-scale precision in their near vicinity and use some other method to move longer distances. Some of these methods are considered later in the experiment conducted by us.

2.4.2 Artificial methods

Artificial locomotion methods are movement methods where the movement is initiated by some action that does not directly correspond to the movement. These include, for example, pressing a button or using the analog stick on a game controller [9].

Controller-based locomotion utilizes methods familiar from traditional game controllers; joystick-, button- or touchpad-based input. The application's input handler maps the movement of a joystick, the directional input of a button, or the touchpad's touched position into a movement vector used to move the user in the virtual space.

Teleportation-based locomotion was first popularized in VR games by The Lab, a game/technology demo by Valve Software released alongside HTC Vive [23]. In the usual implementation, the end of the user's virtual hand projects a Bézier curve or a straight line that the player aims to the location where they wish to move [24, 25]. By pressing some input button on their controller, the application teleports them into the position determined by the line or the curve. Usually, the headset's view is faded into black and then faded in as the transition occurs to reduce motion sickness. Teleportation-based movement is considered one of the safest for people prone to motion sickness but has limitations to what kinds of situations it suits. This is one of the questions we consider later in the thesis.

2.4.3 Continuous and non-continuous

Continuous locomotion methods include locomotion methods where the user's movement is continuous; that is, the user's movement is smooth and uninterrupted [9]. In non-continuous locomotion methods, the user's movement contains "jumps" to different locations. Most of the locomotion methods considered in this thesis are continuous, with two teleportation-based locomotion methods being non-continuous.

3 Game design principles for first-person VR

In this chapter, we explain how the first person perspective and character controllers generally work in games and in virtual reality. We briefly describe the history of first-person character controllers and how they have developed into their current form. We also describe the kinds of locomotion used in virtual reality environments.

3.1 History of first-person character controllers

First-person view in a game means that the player views the environment through the eyes of their in-game avatar [26]. This perspective has been used in games since the 70s and is one of the most common perspectives to this day. In virtual reality, it is the most popular one, as first-person view is how we humans perceive the world around us.

A character controller is a construct used to transfer user input into the movement of the game world object representing the user's character. At the simplest, it is an object that listens to the user's input, and moves itself accordingly. The mechanics of a game are commonly built around the character controller's interaction with the rest of the game world.

The most common control schemes for first-person computer games outside virtual reality are a combination of mouse and keyboard and a gamepad, such as the ones used for video game consoles. In a mouse-and-keyboard input scheme, the player controls the character's look direction with the mouse and the movement usually with the keyboard's keys W, A, S, and D. With gamepads with two analog sticks, the player controls the look direction with the right analog stick and movement with the left one. This is the de facto standard method for first-person locomotion in video games.

Early first-person video games, such as Wolfenstein 3D [27], utilized slightly different control schemes. In many of these, horizontal movement was not as central as it is in the modern standard control scheme.

3.2 Character controllers in virtual reality

First-person view is the most common point of view in virtual reality; however, third-person virtual reality games also exist [28]. First-person viewpoint can be considered a quite obvious choice in virtual reality where the head-mounted displays track the user's head's movements, and a third-person viewpoint requires the program to guide the user to consider some external object to be their "self" [26].

The usual room-scale character controller is a floating head that follows the headset's movement in the room-scale space [25]. If there is a torso, applications usually consider it to be directly below or slightly behind the head, as the commercial virtual reality headsets do not contain means to track the user's body's position separately from the head. The torso collider can be used to detect whether the user should fall off a ledge or not if they decide to walk off one. The headset's collider is usually used to detect collision with walls.

Additional devices, such as the Vive Tracker, can be utilized as extra trackers for objects such as tools or the user's legs [29, 21]. However, locomotion with supplementary devices is outside the scope of this thesis; we focus only on locomotion methods achievable with the most common VR device setup of a headset and two controllers.

3.3 Virtual reality environments

Environments for virtual reality first-person character controllers are usually in a 1:1 scale to the real world, making the player's avatar in the game world the same height as the player is in real life. The environments can be divided roughly into three categories: free-roaming, on-rails, and stationary.

Free-roaming environments allow the player to move freely from place to place. These are the environments we are most interested in in this thesis, as they have the most comprehensive utility and potential for immersion, and are thus the most interesting to discuss. The player has full control over their position in at least two dimensions, allowing them to traverse through the environment by choosing the route they wish.

On-rails environments have the user move through an environment in a vehicle, such as on top of a floating platform, sitting on a chair, or seated in a spaceship's cockpit. The player has limited or no control over the vehicle – it moves along a pre-defined route. In on-rails environments, there is no locomotion per se, and the player's movement is automatic.

Virtual reality rollercoasters commonly utilize on-rails movement.

Stationary environments are small areas, usually only a few square meters, covering approximately the same area as a VR rig's room-scale area. In this case, the entire game takes place within one or several of these areas, transportation between them being teleportation-based. These environments are used in games such as Job Simulator [30], visualized in Figure 3.1, making the user less prone to motion sickness than other environment types, as the player's room-scale movement initiates all locomotion.

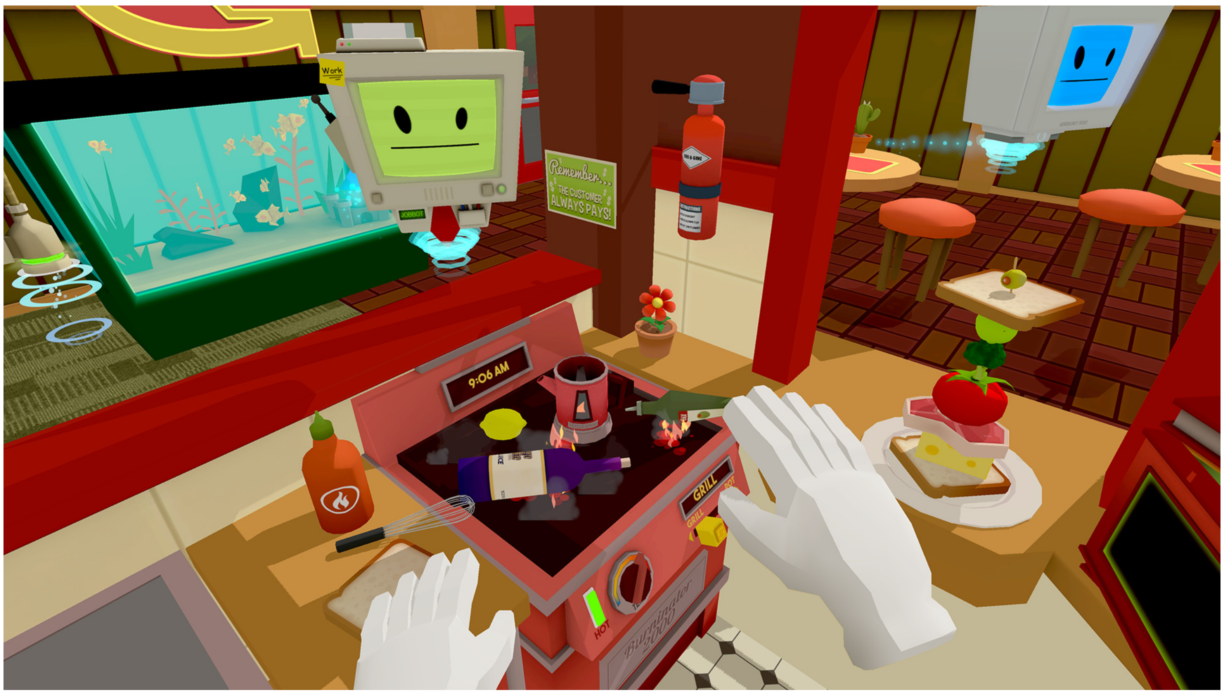

Figure 3.1: Job Simulator is one of the launch titles of HTC Vive [31]. It utilizes a room-scale environment, where the user can move around a virtual room by moving in the physical space. The user's viewpoint corresponds to the location of the headset, and the position and rotation of the virtual hands corresponds to those of the two controllers. By pressing the trigger buttons on the controllers, the user can open or close the virtual fingers and grab objects.

4 Experiment

In this chapter, we describe the methods used in our experiment, how the virtual environment was constructed, and the experiment setup.

4.1 Experiment setup

Multiple surveys exist that aim to collect and categorize the locomotion methods currently in use in games [9, 32]. For the experiment conducted in this thesis, we picked a pool of locomotion methods that consists of both artificial and physical locomotion methods and includes both popular ones and more experimental attempts at creating immersive movement. These locomotion methods are modified versions of the locomotion methods provided by the VRTK (Virtual Reality Toolkit) framework version 3.3.0, developed by Extend Reality Ltd for the Unity game engine [25, 33]. These locomotion methods are described in more detail in the next section.

As room-scale locomotion is available in most current consumer headsets, either with an inside-out method or with base stations, we utilize room-scale locomotion in conjunction with all of the other locomotion methods.

The environments created for this experiment were designed to represent a wide variety of different situations that might arise in a virtual reality game. They represent scenarios where the user has to navigate varying environments, and in later stages also to react to moving environmental obstacles.

The pools of locomotion methods and environments selected for this experiment are by no means exhaustive; we settled on pools sized so that the experiment would last less than one hour for each user. By adding more locomotion methods and more environments, the time requirement for the experiment would have increased considerably. The pool consists of four artificial and three physical locomotion methods.

The experiment is run using a setup consisting of the HTC Vive headset, two HTC Vive wand controllers, two base stations, and a desktop PC running the experiment software. The VR setup is in a room with a 2,4 meters x 2,4 meters area for room-scale movement. It is connected to the PC with a cable running from the headset's back into a link station next to the computer.

4.2 Locomotion methods

In the experiment, we aim to gauge how suitable the selected locomotion methods are for the different game scenarios. The considered locomotion methods are:

Artificial

- Teleportation with the screen fading black (*blink teleport*). Artificial, non-continuous.
- Teleportation with the user seeing movement when teleporting (*dash teleport*). Artificial, non-continuous.
- Touchpad-based movement (*touchpad*). Artificial, continuous.
- Touchpad-based movement with rotation control (*touchpad with rotation*). Artificial, continuous.

Physical

- *Drag world*, where the user can drag themselves around the environment by grabbing air with their controllers. Physical, continuous.
- *Arm swinger*, where the user swings their arms to move. Physical, continuous.
- *Step multiplier*, where the user can multiply the distance they walk in room-scale by pressing a button. Physical, continuous.

4.2.1 Blink teleport

In blink teleport, the user touches a haptic surface (in this case, the HTC Vive controller's touchpad), enabling the aiming reticle. The user can cancel this action by stopping touching the surface. While the aiming mode is enabled, a curve appears from the end of the user's controller, with the other end touching the ground in the virtual environment, and displaying a circle in that position. In our implementation, when the user presses the touchpad, the screen fades to black for 2 seconds, repositions the user to the circle's position, and fades out over another 2 seconds. The user's orientation stays the same, and the user can control their rotation with physical movement. The user has no artificial limit on how often they can perform this action. The maximum range for the aiming curve is 6 meters. The fading in and out is used to increase user comfort [24]. This locomotion method is commonly used in virtual reality games, such as Rec Room and Half-Life: Alyx [34, 35].

4.2.2 Dash teleport

Dash teleport, sometimes called shift teleport [36], works similarly to blink teleport, but instead of the screen fading to black, the camera jumps to the new position over 1 second by interpolating the initial and the target locations. This visible jump aims to make the movement more apparent to the user, as having the environment simply change as it does in blink teleport does not convey movement. This variant of the teleportation locomotion method is somewhat rarer than blink teleport but is often implemented alongside it in virtual reality games, such as Half-Life: Alyx [35].

4.2.3 Touchpad-based movement

Touchpad-based continuous movement works similarly to analog stick-based movement in most first- and third-person non-VR games. By touching the touchpad, the user can adjust the movement vector of their virtual avatar. When touching the upper part of the touchpad, they move forward; touching the lower part makes them move backward. The left and right sides of the touchpad allow for horizontal strafing. To rotate themselves, the user has to physically turn in real space. The movement direction is defined by the direction of the user's headset. The closer the user's thumb is to the center of the touchpad, the slower they move. Additionally, faster movement can be achieved by touching both controllers' touchpads. In this case, the movement vectors created by the touchpad input are added together; thus, the movement direction is the average of the two directions. This speed boosting feature is specific to the VRTK implementation, and might not be included in other implementations [25].

Touchpad-based movement is a very basic locomotion method, and like blink teleport, it is available in almost all virtual reality games. It is a VR-specific variant of a classic video game locomotion system.

4.2.4 Touchpad-based movement with rotation

Similar to the other touchpad-based locomotion method, but the horizontal strafing is replaced by rotation. While using this locomotion method, the user is asked not to turn in the real world, but to keep their feet pointing in the same direction for the scenario's duration.

This locomotion method is available in VRTK [25]. This is a locomotion method that can be used while sitting, and in this way, it is more accessible and less physically demanding than the other locomotion methods, which is why we decided to include it. However, this can be limiting; the effects of this is discussed further in the results.

4.2.5 Drag world

In drag world locomotion, the user can move by "grabbing" the virtual world with their controllers, pressing both of the trigger buttons on the HTC Vive controllers. The locomotion method does not require the user to grab an actual item within the virtual environment; they can also take hold of the air. While grabbing, the user can move their arms to drag themselves inside the game world. This action can be likened to climbing or using ski poles while skiing. In this experiment, gravity still applies to the user, so they can only move along the ground, not climb into the air. The magnitude of movement caused by dragging is amplified by a factor of 4, to increase the user's movement speed in large environments, to match its speed with other locomotion methods, and to make it more viable in a wider variety of situations. We consider the positive and negative effects of this in more detail in the results. The drag world locomotion method is uncommon but available in some commercial games, such as Panoptic and Gorn [37, 38].

4.2.6 Arm swinger

Arm swinger is a locomotion method where the user touching both controllers' touchpads enables movement mode. While in movement mode, the user can move around the virtual environment by swinging their arms, as if they were walking [22]. This act aims to reduce motion sickness by simulating movements made when actually walking. The movement direction vector is calculated from the average rotation of both controllers. The speed of movement is defined by the speed the user swings their arms, ranging from almost unnoticeable to running speed. This locomotion method is somewhat similar to the walk-in-place locomotion, but instead of utilizing a tracker attached to the user's leg, it utilizes the user's hand motions tracked by the controllers [21]. The arm swinger locomotion is not very widely adopted, but is available in some virtual reality games such as Sprint Vector [39].

4.2.7 Step multiplier

In step multiplier locomotion, also known as "Seven League Boots" locomotion [40], the user moves around the environment by walking physically in the room-scale environment. This locomotion method aims to simulate actual walking as closely as possible and is the only one that utilizes the user's (non-tracked) legs. Because the room space is physically limited, a step multiplier functionality is implemented. In the VRTK implementation we use [25], when touching both controllers' touchpads, every movement the user makes in the room-scale space is amplified by a factor of 6, if their movement speed crosses a threshold. This allows the user to walk long distances in the virtual space, while still moving only short distances in real-world space. This locomotion method requires the user to be aware of the real-world room's limits and adjust their position accordingly when reaching a wall.

4.3 Environments

For this experiment, we constructed an environment in the Unity game engine, consisting of five different scenarios. The environment was constructed in Unity version 2019.3 utilizing the built-in ProBuilder tools. The five environments are described in the next subsections.

The order of the environments was chosen so that the first scenarios are slow-paced and let the user get used to the current locomotion method. The later environments are placed in order of increasing complexity, leaving the most complex block-dodging puzzle for the last. This way, the user does not immediately get overwhelmed by challenging situations.

The shortest path through all of the environments is approximately 300 meters, but the chosen path varied somewhat between users. Some interesting notes on this are discussed further in the results, in Subsection 5.3.3.

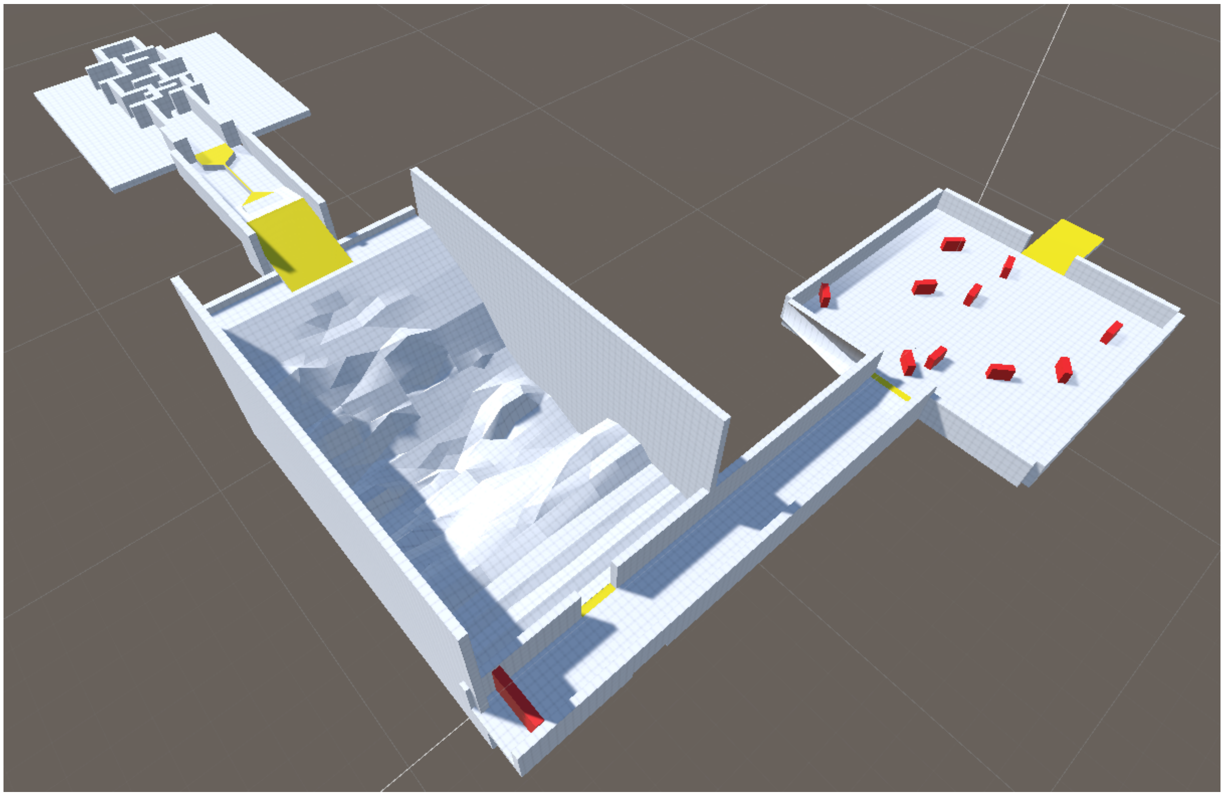

Figure 4.1: The virtual environment constructed for this experiment. Each square in the textures corresponds to one square meter.

4.3.1 Maze

A simple, linear maze without branching. The user is instructed to reach the other end of the maze by traveling through it. The corridors are 1 to 3 meters wide, and the shortest route through the maze is approximately 35 meters long. The layout of the maze can be seen in Figure 4.2.

This scenario's idea is to test the locomotion method in a situation where spaces are narrow, many corners exist, and the user cannot see very far. The goal of this is to test the user's spatial awareness, and how the selected locomotion method affects it. Many games contain indoor scenes, where the user has to pay close attention to their surroundings to advance. This scenario aims to simulate these kinds of environments.

4.3.2 Bridge

The second environment is a 30 cm wide bridge that the user is instructed to cross. This scenario is used to measure how precisely the users can use the current locomotion method

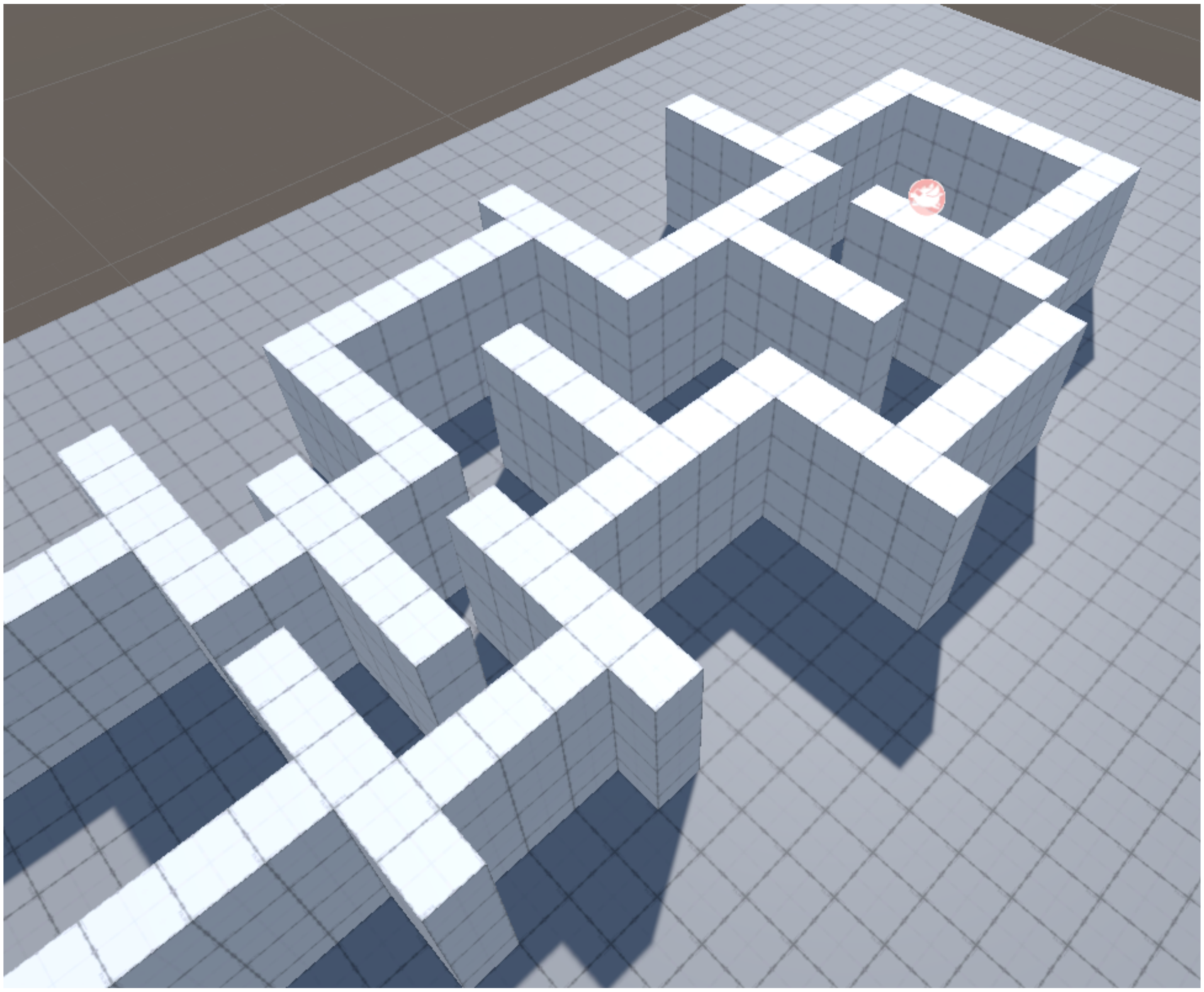

Figure 4.2: First stage of the obstacle course: A simple maze with no dead ends. The route is made clear to the user, putting the focus on environmental awareness and precise movement. The starting position is at the icon at the top right corner, and the exit towards the next stage is at the bottom left.

to move. The bridge is visualized in Figure 4.3.

Falling off the bridge simply drops them onto a platform, from where they can continue onwards. This drop is just 1 meter, to prevent unnecessary discomfort. If the user falls off the bridge, they are instructed to simply move forward, as resetting the scenario creates additional movement and possible physical discomfort and requires more time.

The bridge can also be considered an exciting gameplay situation. Many games test the player's ability to do precise tasks requiring practice and skill. This bridge also tests the user's precision after getting used to the locomotion method in the first environment.

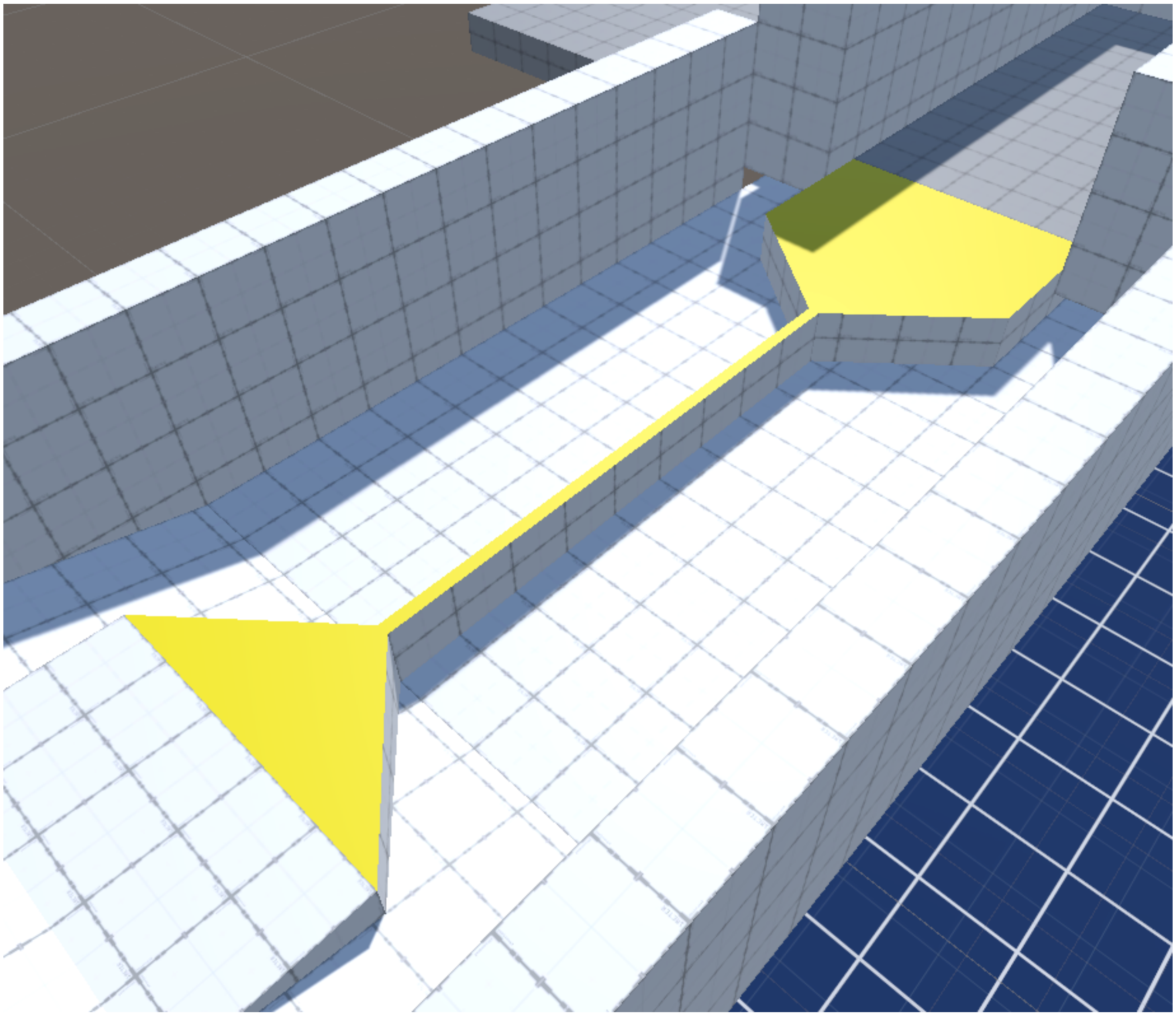

Figure 4.3: The second stage is a 30cm wide bridge, 9 meters long. Requires precise movement to cross successfully. If the user falls off, they can continue to the next stage.

4.3.3 Slopes

The third environment is a wide, open area with uneven terrain. It is 30 meters wide and 80 meters long. It is divided into two halves, where the first one descends into a "valley," and the second half rises again. The user is instructed to reach the door on the top on the other side. An overview of this environment can be seen in Figure 4.4.

This scenario is used to test how the users behave in a situation where the ground below their feet is uneven, and its shape does not match the flat floor they stand on in the real world. In realistic environments, most often ones that represent outdoor scenes, the ground is seldom perfectly flat. This scenario creates a gameplay situation where the user

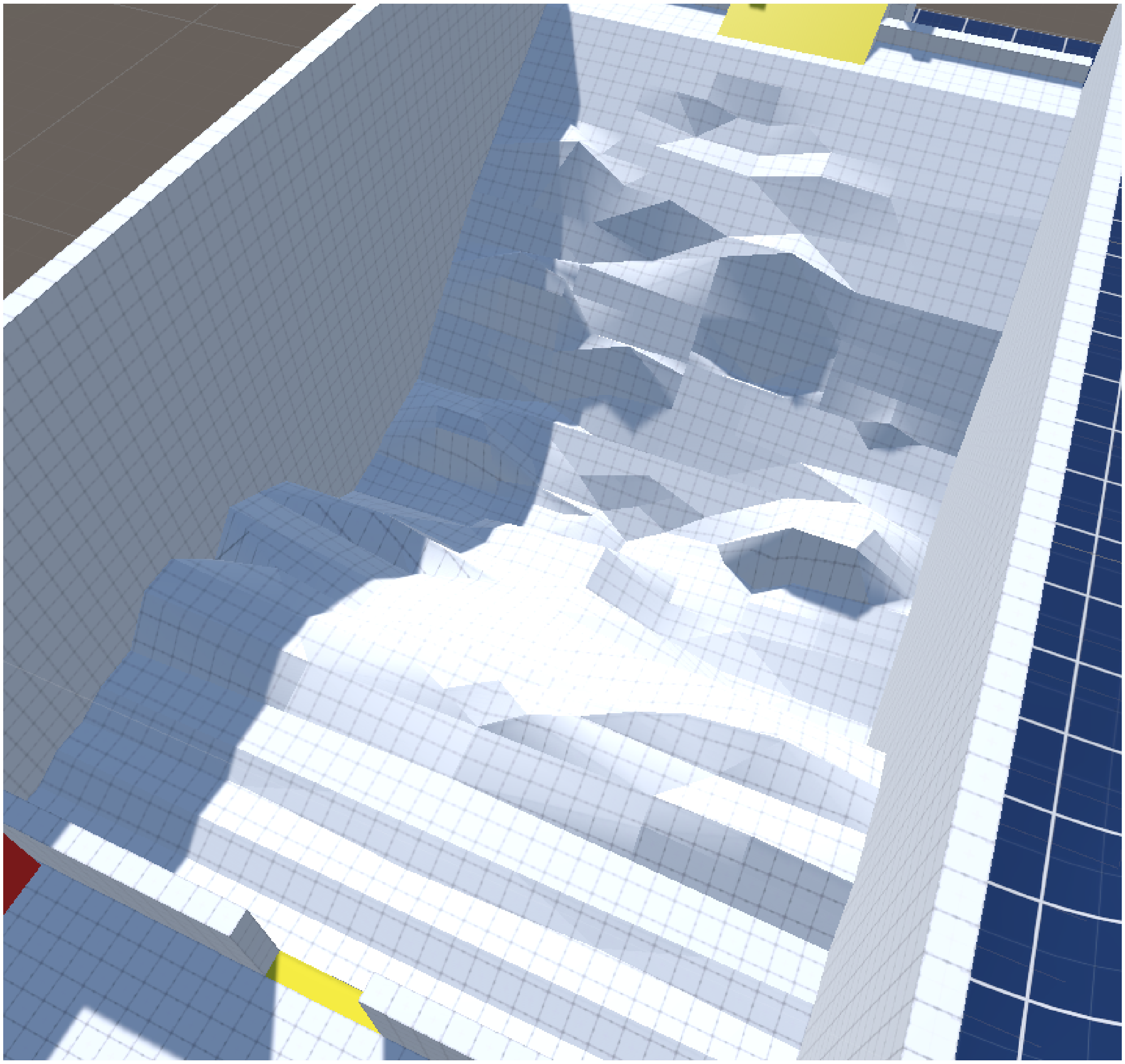

Figure 4.4: The third stage is has uneven ground, first sloping down into a "valley" and then rising up.

has to find a possible and comfortable route to move through, as walking up too steep a slope (over 45 degrees) causes them to slide back down.

4.3.4 Moving wall

In this scenario, the user is in a 50-meter long tunnel in which they are instructed to run away from a red-colored moving wall that comes from behind them. The wall cannot be dodged and is as wide and tall as the tunnel itself. The wall moves at a slow pace, at about 1 meter per second, and slows down further when it is about to reach the user. This gives them more time to react. This tunnel is visualized in Figure 4.5.

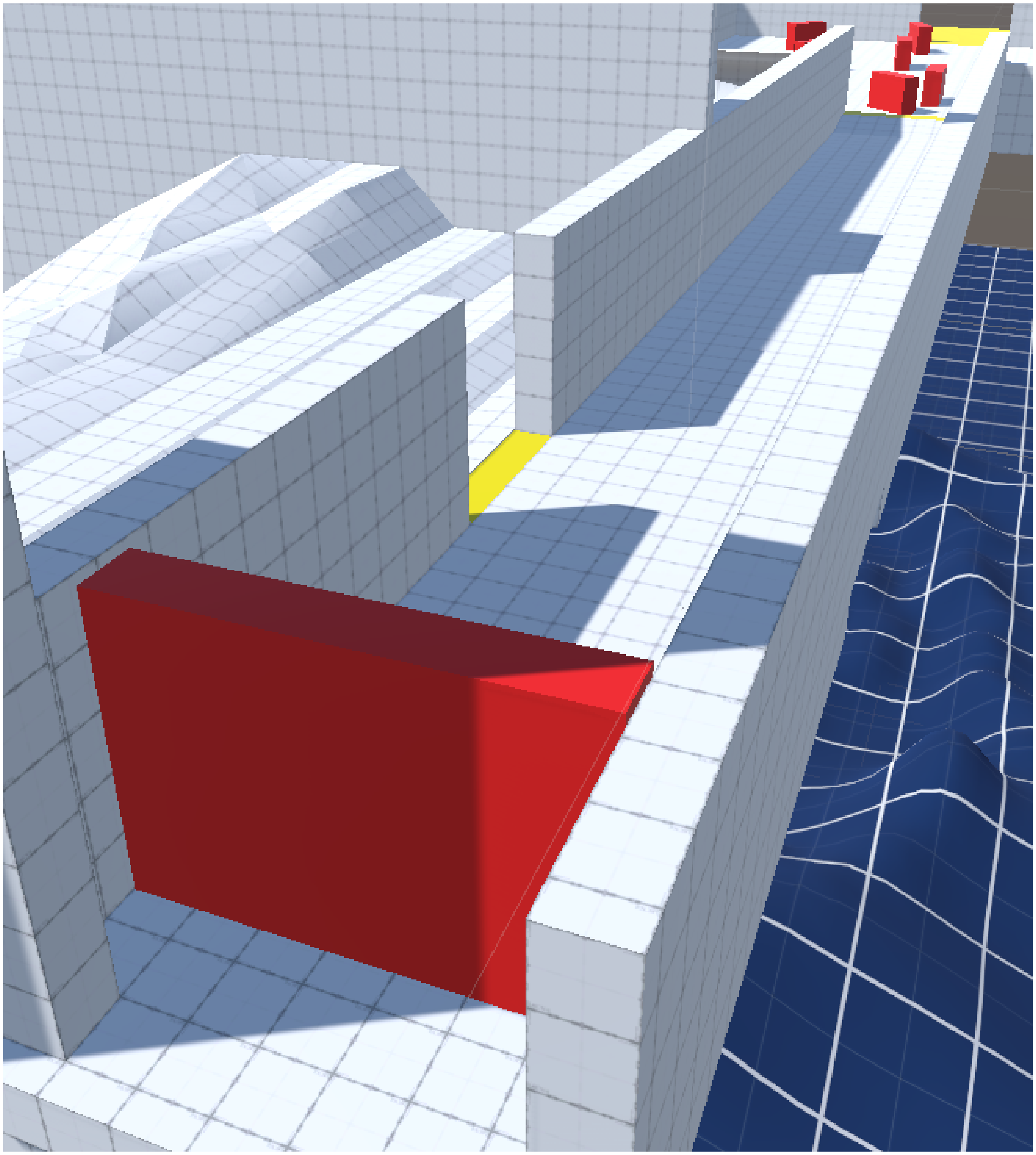

Figure 4.5: The fourth stage is a tunnel with a wall that starts moving slowly when the user crosses the yellow line into the room. The user is instructed to run away from the wall along the tunnel.

This is a scenario where the user has to move away from the wall as fast as possible using the current locomotion method. Unlike the previous scenarios, where the user may plan their movement as much as they wish, this scenario requires the player to react to a changing environment. If the wall catches the user, it disappears, and the user can continue forward. Hits of the wall are recorded in the results. The wall also disappears when the user reaches the end of the tunnel.

This scenario simulates a chase scene, where the user has to run away from danger. These are common in regular video games but rarely appear in virtual reality games because common locomotion methods are poorly suited to this kind of movement. In this experiment, we aim to gauge the user's engagement in this situation with our different locomotion methods.

4.3.5 Moving blocks

The fifth and the last environment is a square 900m^2 room, where 12 randomly positioned red-colored blocks, each 1 meter wide, 3 meters long, and 2 meters tall, move in circles with a radius of 8 meters with a speed of 3 meters per second. These blocks are large enough that the user has to utilize the locomotion method to avoid them, and their routes are predictable enough that it is possible to plan movement around them. The user is instructed to get past them and reach the goal area at the other end of the room. This environment is visualized in Figure 4.6.

This scenario tests the user's ability to dodge moving objects utilizing the current locomotion method. The user has to constantly observe their surroundings, as the paths of the blocks cross so they might have to dodge multiple blocks simultaneously. This also tests how the locomotion method affects the user's spatial awareness. The blocks pass through the user if collided with, but the number of times the user gets hit is recorded in the results.

This scenario simulates environmental hazards, such as moving cars or projectiles. Dodging moving items has long been a source of exciting gameplay, but like the chase scene depicted by the tunnel, it is not trivial to make engaging with virtual reality locomotion.

The five environments are chained together in this order. Simple passageways connect the environments directly to each other. The user begins from a closed room at the beginning of the maze, and their goal is to reach a yellow platform beyond the moving red blocks.

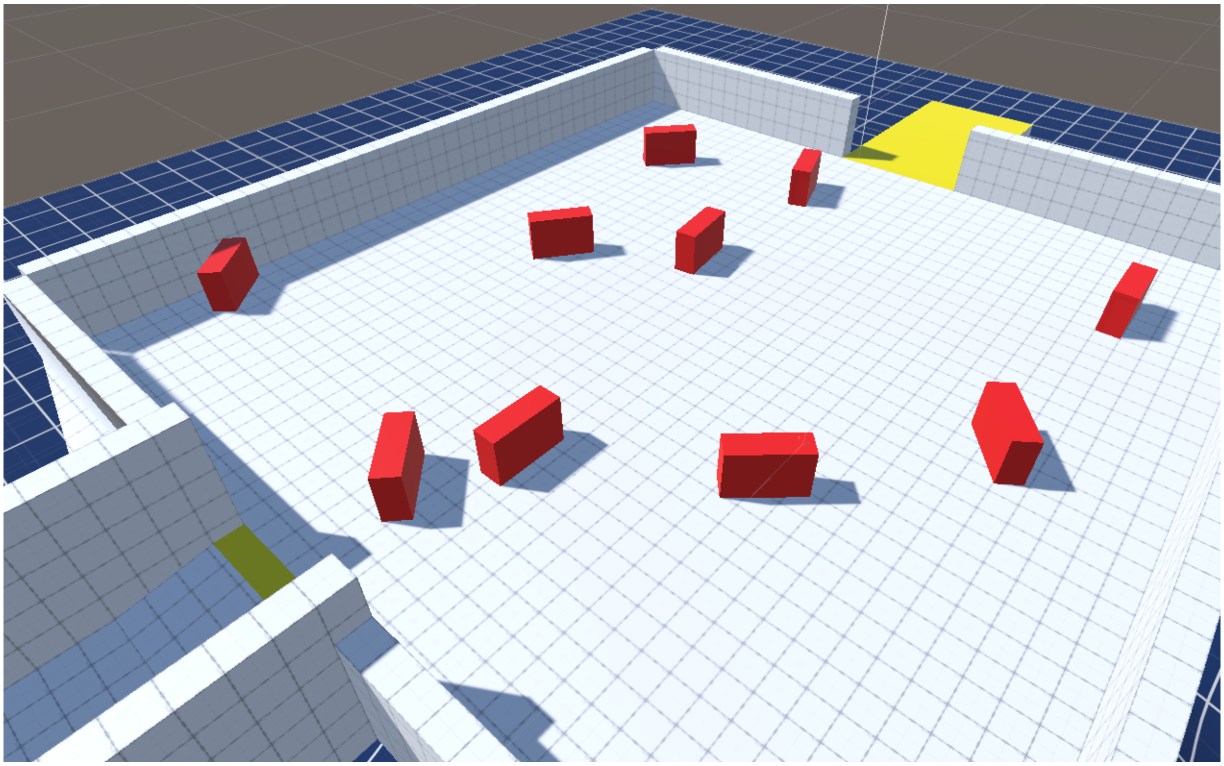

Figure 4.6: The last stage is an open area with red blocks that move in circles.

4.4 Evaluation axis

Results are collected from the participants in the form of an interview with multiple-choice questions and open questions. Most of the questions were asked on a per-locomotion method basis, after the playthrough but before switching to the next locomotion method. The users were also encouraged to provide verbal commentary whenever they felt like it.

For the first three questions, the participants were asked to reply with a number from 1 to 5 (with half points allowed, making this effectively a 9-step scale) and optionally, a verbal description. The three main questions and the ranges of 1 to 5 described to the users are:

- How easy was this locomotion method to learn?
  - 1: impossible to use.
  - 5: immediately clear how to use.
- How immersive did this locomotion method feel?
  - 1: you constantly had to think about the locomotion method; it was very unnatural.

    - 5: you did not think about the locomotion method at all; it felt perfectly natural.

- How much motion sickness did this locomotion method cause?
    - 1: impossible to use.
    - 5: none at all.

The aim of the first question, “how easy was this locomotion method to learn,” is to gauge the intuitiveness of each locomotion method. A locomotion method with a rating of 1 is next to impossible to use for the user, either requiring physical effort, fine motor control, or mental effort to keep track of how to move. A locomotion method with a rating of 5 is straightforward and intuitive to use, requiring little explanation and almost no time to get used to.

The second question, “how immersive did this locomotion method feel,” aims to measure how realistic and natural the locomotion method feels. A locomotion method with a low rating requires the user to constantly take it into account and consciously think about movement. Locomotion methods with a high rating quickly become second nature to the user and are easy to use with little mental effort.

The third question, “how much motion sickness did this locomotion method cause,” gauges the level of physical discomfort caused by the locomotion method. A locomotion method with a rating of 1 causes so much discomfort that it is almost impossible to use. A locomotion method with a rating of 5 feels comfortable, even when performing fast movement and rotation.

Additionally, the participants were asked how they felt about the gameplay parts of the environment; the maze, the bridge, the slopes, the tunnel, and the moving blocks. They were asked for a free-form description of which parts of the environment were the most fun and exciting to explore with the current locomotion method.

At the end of the experiment, the participants were asked how often they used virtual reality devices using the following scale:

- Never before.
- Once per year or less.
- A couple of times per year.

- At least monthly.
- At least weekly.

Finally, the participants were asked about which of the tested locomotion methods was their favourite, which one they would pick for daily use. These results can be seen in Table 4.1 and are discussed further in the discussion chapter.

4.5 Running the experiment

In this section, we describe how the experiment was conducted. This can be seen in a flowchart form in the Figure 4.7, showing the process for a single participant.

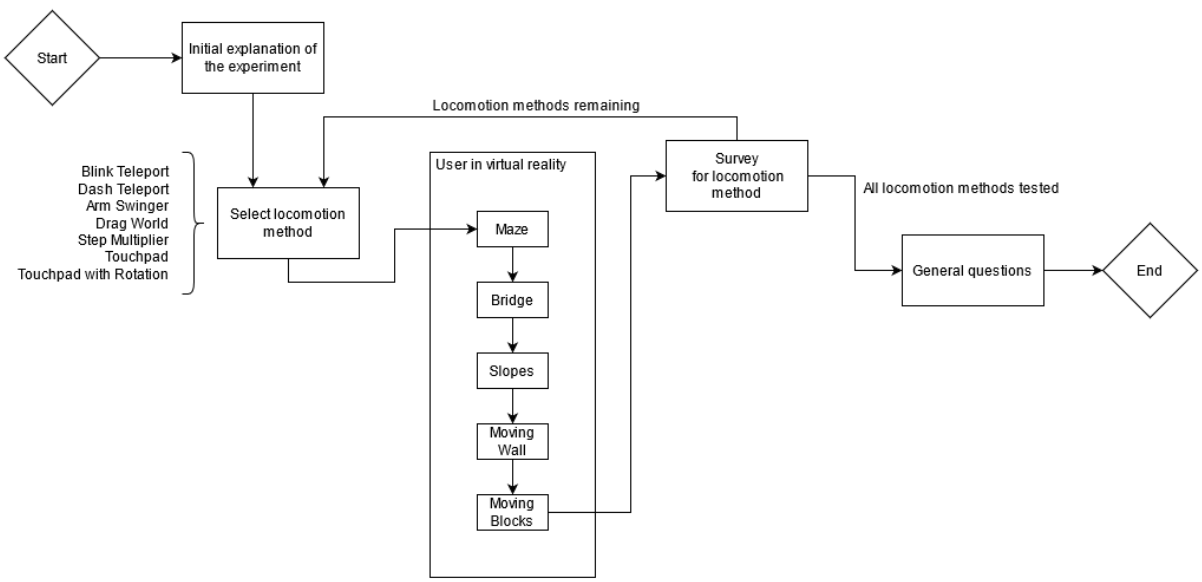

Figure 4.7: Flow of the experiment. The process presented here was conducted for each of the 10 participants.

The experiment was done in a room with a 2,4m x 2,4m space defined for the room-scale setup. On three sides, the space was limited by a wall; on the fourth side, there was a table with the PC that was running the VR experiment software.

The experiment subjects were ten 24-35-year-old students with personal experience in virtual reality ranging from weekly use to never before. The students were computer science, data science, history, and game design majors. The experiment took on average 45 minutes per person. This user pool is more technologically skilled than the average user, but their experience in video games and virtual reality still varied considerably.

User ID	How often do you use VR devices?	Favourite locomotion mechanic
1	Once per year or less	Dash Teleport/Touchpad
2	A couple of times per year	Blink Teleport
3	At least weekly	Arm Swinger/Touchpad
4	A couple of times per year	Blink Teleport/Arm Swinger
5	A couple of times per year	-
6	At least monthly	Dash Teleport
7	A couple of times per year	Touchpad with Rotation
8	A couple of times per year	Arm Swinger
9	A couple of times per year	Touchpad/Arm Swinger
10	Never before	Arm Swinger

Table 4.1: The group of users in this experiment.

Backgrounds of these users can be seen in Table 4.1. This table also contains the users' preferred locomotion methods after the experiment; these are referred to in greater detail in the discussion chapter. We identify these users later in the thesis with ID numbers seen in Table 4.1.

At the beginning of the experiment, the subjects were explained that they would go through a five-stage obstacle course with seven different locomotion methods. Feedback and commentary during the experiment from their part was encouraged, but not required. In these results, we note how many users sounded a certain opinion, but this does not necessarily mean the rest of the users had opposing opinions. The users were told that it was okay to stop the experiment at any point if they felt too much discomfort, but none of the users invoked this.

The five sections of the VR environment were presented to each user in the same order, but the order of locomotion methods was randomized. The order of the sections was in increasing mechanical difficulty. The locomotion method order was random to mitigate the effect of the previous locomotion method affecting the experience in the next one, as some locomotion methods, such as the two teleportation systems, were close to each other motorically.

If a user exited the bounds of the obstacle course, they were teleported back into their last valid position in the obstacle course. This happened three times, two of which were caused by the user 4 testing the limits of the blink teleport method, and once by accident by user 7 with the drag world method.

5 Results

The results of the experiment were collected in a spreadsheet. They were logged after each locomotion method. A script in the Unity engine was used to measure the time spent in each environment in seconds. The script logged elapsed time whenever the user crossed a pre-defined border between two environments, situated on top of a yellow floor.

First, we look at the scores the users gave each locomotion method in the three categories we refer here to as *ease of use*, *immersiveness* and *comfort*. Then we will go through each locomotion method, making observations on each of them based on the users' comments and test results. After this, we will consider each section of the obstacle course separately and discuss the compatibility with different locomotion methods in more depth based on the users' comments about the locomotion methods' suitability to the sections.

5.1 Score results

The average scores for each locomotion method can be seen in Table 5.1. According to these averages, blink teleport and dash teleport achieved the highest scores in ease of use, both reaching 4.6/5. These locomotion methods did not cause much difficulty for any user. Step multiplier locomotion got the lowest score, 2.2/5. In immersiveness, arm swinger reached the highest score, 4.1/5. Step multiplier got the lowest score, 1.8/5.

In motion sickness, blink teleport gained the highest score of 4.2/5. Dash teleport came second with a score of 4.1/5, slightly lower, because the transition caused some users discomfort. The lowest score in this category was given to drag world locomotion. Multiple users felt that the rotation feature caused a lot of discomfort and did not feel good to use.

5.2 Observations on locomotion methods

In this section, we go through each locomotion method and describe how the users felt about each one, based on both their verbal comments and numerical evaluations. Based on these, we make general observations. As the number of participants is somewhat low, broad generalizations are not meaningful to make.

Average Scores	Ease of Use	Immersiveness	Comfort
Blink Teleport	4.60	2.55	4.20
Dash Teleport	4.60	3.10	4.10
Touchpad	4.10	3.00	3.50
Touchpad with Rotation	3.80	3.20	3.05
Drag World	3.25	2.85	2.80
Arm Swinger	3.60	4.10	3.10
Step Multiplier	2.20	1.80	3.15
Average	3.74	2.94	3.41

Table 5.1: Average scores for each locomotion method, on the 1-5 (with half points) scale. The teleportation methods were generally considered the best regarding ease of use and lack of motion sickness, whereas the arm swinger locomotion method was regarded as the most immersive. The step multiplier locomotion method took the last place in both ease of use and immersiveness, but the users felt it caused less motion sickness than drag world.

5.2.1 Blink teleport

The blink teleport locomotion method was generally considered good and easy to use, as seen in Table 5.2. Two users, 1 and 9, commented that estimating the moved distance was difficult, and user 8 commented that they had to put a lot of effort into aiming the reticle. Three users commented that the teleportation felt disorienting, especially in cramped spaces, as the entire environment changed whenever the teleportation was activated. Paris et al. have concluded that discrete locomotion methods, such as teleportation, make it more difficult for the user to track their own movement compared to continuous locomotion methods [41]. This is clearly seen in effect here.

The users also felt that blink teleportation was boring and static, with which it was difficult to find any enjoyment in locomotion-related tasks. User 9 commented on how it was easy to do huge, spontaneous leaps when panicking because of an environmental hazard. Users 1 and 3 also traveled through the environments very quickly. Because it was easy to move around a lot very fast, they did not spend very much time focusing on their surroundings. This had a negative effect on their level of immersion.

Figure 5.1 shows how much time the users spent in different environments with blink teleport. The figure demonstrates how the teleportation locomotion methods can cause great variation in how much time users spend moving. User 3 cleared the entire course in less than 45 seconds, whereas user 2 spent nearly three minutes.

Blink Teleport	Ease of Use	Immersiveness	Comfort
User 1	4	2	2
User 2	5	3	3
User 3	5	2.5	5
User 4	5	3	5
User 5	5	2	4
User 6	5	2	3
User 7	4	2	5
User 8	4	3	5
User 9	4	2	5
User 10	5	4	5

Table 5.2: Score results for blink teleport.

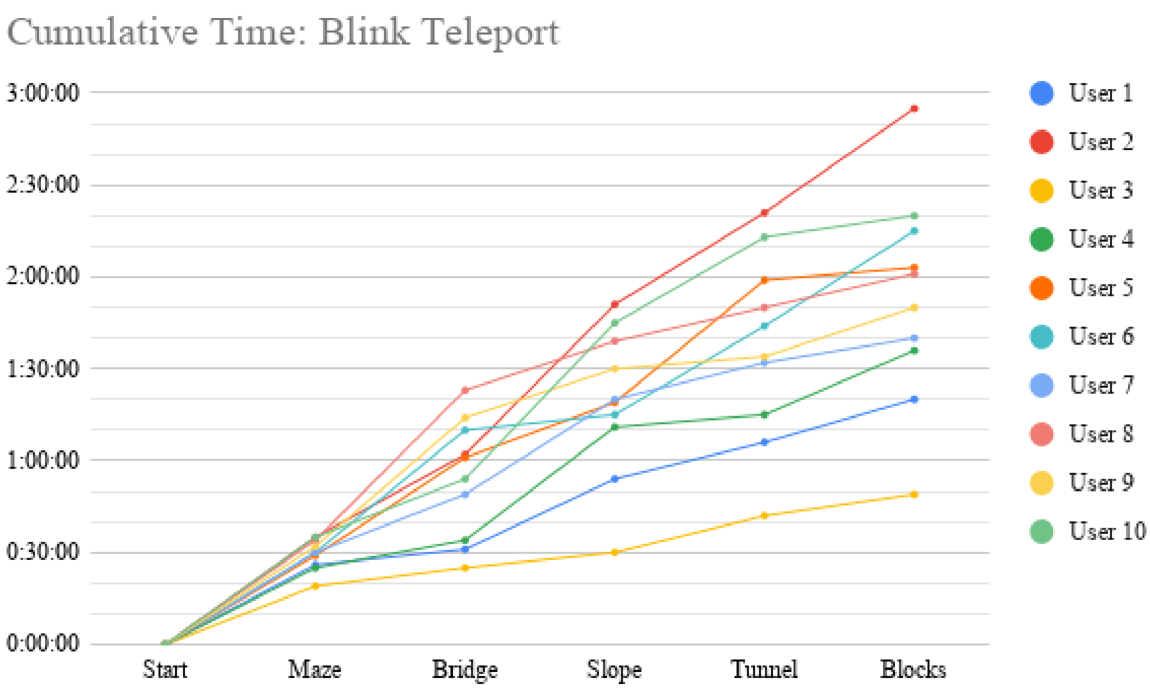

Figure 5.1: Cumulative time for each user with the Blink Teleport locomotion method.

5.2.2 Dash teleport

The dash teleport method was reviewed as slightly more immersive than the blink teleport by most users. Two users specifically commented that seeing the movement makes the

Dash Teleport	Ease of Use	Immersiveness	Comfort
User 1	5	4	4
User 2	5	4	4
User 3	5	3	4
User 4	5	3	4
User 5	5	2	3
User 6	4	4	4
User 7	4	3	5
User 8	4	3	4
User 9	4	3	4
User 10	5	2	5

Table 5.3: Score results for dash teleport.

locomotion method more immersive than the blink teleport. According to these same users, it felt less disorienting than blink teleport, as they could more easily understand and visualize the movement as it took place. However, from an immersion perspective, the users commented that even though dash teleport visualized movement, it still felt lifeless and static, as though the player was a statue sliding around the environment. The score results for each user can be seen in Table 5.3.

User number 4 was able to get themselves out of the obstacle course's bounds twice by pointing the aiming curve at unexpected positions. The teleportation locomotion methods provide much freedom to where the user can move. Because of this, the level designers need to take care in designing the environment so that the teleportation curve does not allow the user to move into unintended locations, or that these areas are flagged as invalid targets for teleportation. This is especially important for games that provide teleportation as an alternative locomotion method to linear locomotion methods, because they cannot be used to scale walls or cross wide gaps, as teleportation can.

Figure 5.2 shows how much the users spent time in different environments with dash teleport. This chart also demonstrates how it is possible to move through areas very quickly with teleportation, as user 4 cleared the course in 30 seconds.

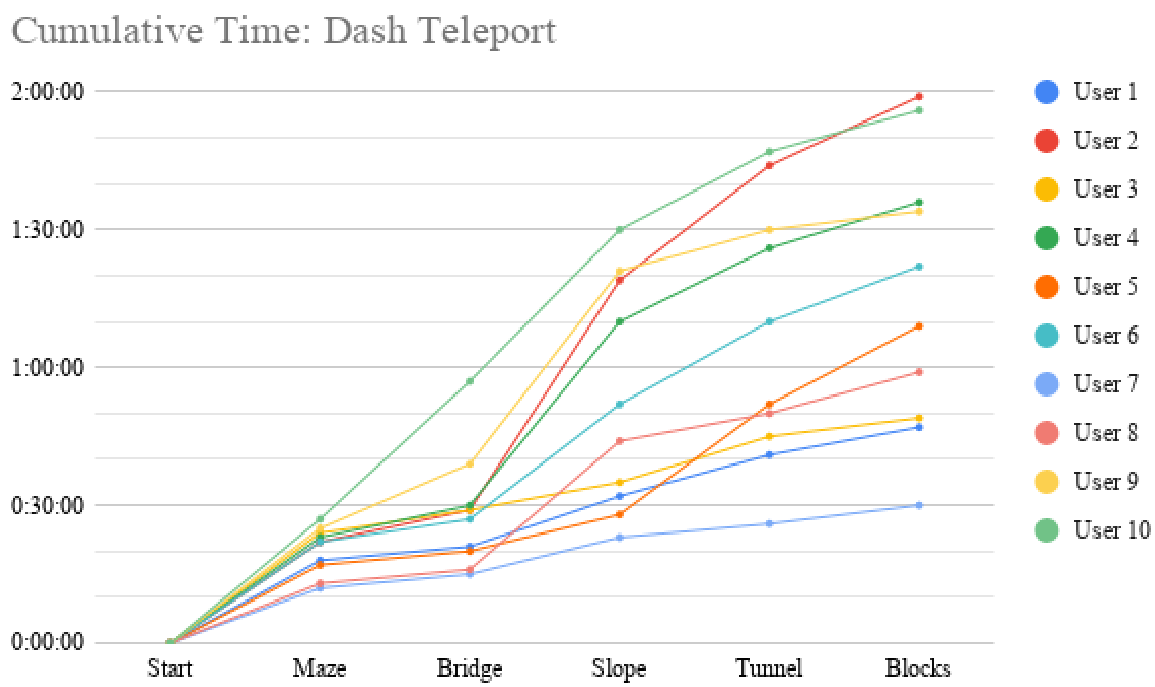

Figure 5.2: Cumulative time for each user with the Dash Teleport locomotion method.

5.2.3 Touchpad-based movement

The basic touchpad movement was also considered to be one of the best. While it had the effect of causing motion sickness in some users, it was considered intuitive and straightforward, especially by those with a previous background in video games. The metaphor of traditional joystick movement was familiar and intuitive. The score results for each user can be seen in Table 5.4. These results show that the amount of motion sickness caused by touchpad locomotion varied greatly, with user 4 giving it a score of 1. Other users seemed almost immune to locomotion sickness with this locomotion method, with two of them, 3 and 5, giving it full points.

The users, however, felt more disconnected to the game environment compared to the physical locomotion methods, but not as much as with the teleportation locomotion methods. Users 1 and 9 commented on how the movement direction being tied to the user's headset's direction prevented them from moving and looking around at the same time naturally, and would have preferred the movement direction being based on the controller's direction instead. The movement direction changing with the user's look direction caused considerable motion sickness to users 4 and 9.

Touchpad	Ease of Use	Immersiveness	Comfort
User 1	4	4	4
User 2	4	3	3
User 3	5	3	5
User 4	2	2	1
User 5	5	2.5	5
User 6	4	3.5	3.5
User 7	4	3	4.5
User 8	4	2.5	3
User 9	5	4	3
User 10	4	2.5	3

Table 5.4: Score results for touchpad locomotion.

User 4 commented that it was hard to make precise movements, whereas two others, 3 and 10, had the opposite opinion. These two described it as natural, accurate and intuitive. User 9 likened the feeling to skateboarding. Moving long distances with this locomotion method, such as when escaping the wall, was considered boring by most. However, dodging the moving blocks was considered fun by four users. Figure 5.3 shows how much the users spent time in different environments with touchpad locomotion.

5.2.4 Touchpad-based movement with rotation

Touchpad-based locomotion with rotation was widely considered exciting and different, but unsuitable for general use. Most users likened the feeling to being in a carriage or a car. The rotation speed was considered too slow by users 4 and 7, making turning difficult for them. User 7 also considered the movement speed to be too slow, which made the locomotion method tedious to use. The score results for this locomotion method can be seen in Table **??**.

This locomotion method could be used if the game mechanics were designed around it, with users 3 and 7 seeing potential in it. An interesting proposal from user 7 was to utilize it in a game where the player character sits in a wheelchair. Figure 5.4 shows how much the users spent time in different environments with touchpad with rotation locomotion.

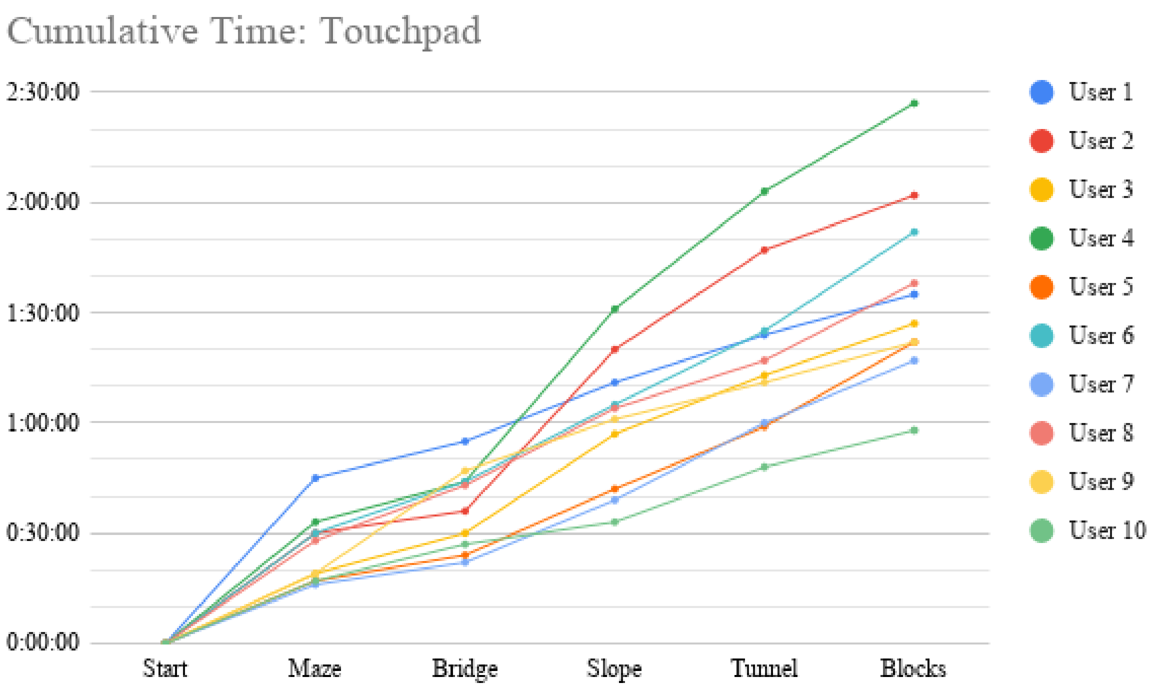

Figure 5.3: Cumulative time for each user with the Touchpad locomotion method.

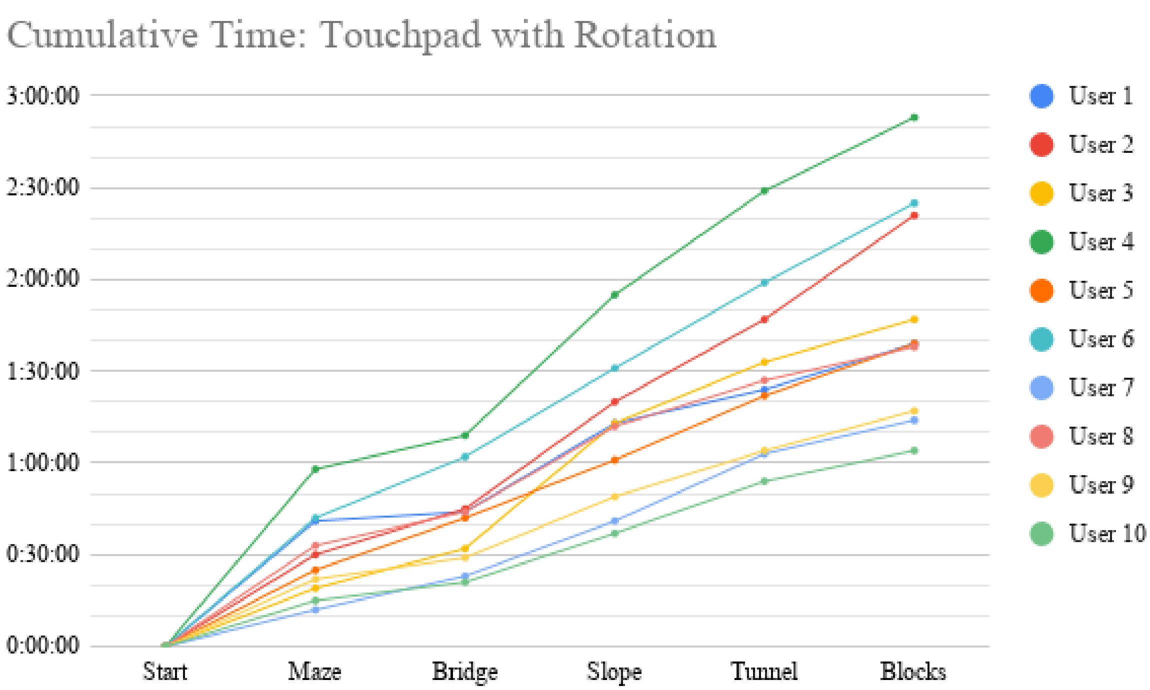

Figure 5.4: Cumulative time for each user with the Touchpad with Rotation locomotion method.

Touchpad with Rotation	Ease of Use	Immersiveness	Comfort
User 1	3.5	5	1
User 2	4	3	3
User 3	3.5	4	5
User 4	3	1	1
User 5	4	2	3.5
User 6	3.5	3	3
User 7	4	4	5
User 8	4.5	3	3
User 9	3	3	2
User 10	5	4	4

Table 5.5: Score results for touchpad with rotation.

5.2.5 Drag world

The drag world was divisive in how easy it was to use, as seen in Table 5.6. The idea was difficult to grasp for seven users, and three users felt that especially the initial maze was complicated to navigate with this locomotion method. Later on, in more open spaces, it felt better. Three users also felt that moving long distances with this locomotion method was tedious, as the arm movement required considerable physical effort.

User 10 commented on how the locomotion method put too much focus on the user's hands, and did not like that the user's head had no role in locomotion at all. This made the locomotion feel unnatural to them. User 3 commented that doing precise movements was very difficult.

However, users 2 and 7 described the drag world locomotion surprisingly immersive after getting used to it. Most users found the rotation mechanism of moving both hands to rotate the user's avatar too difficult. User 9 described that this locomotion method was like an external entity moving the player, and did not feel like they were moving themselves. User 10 suggested having inertia for the avatar's body would make this locomotion method more interesting to use. User 5 commented that the locomotion method felt like skiing. User 7 managed to escape the obstacle course's bounds by dragging themselves through a wall in a way that the collision detection did not catch.

For the action sequences, drag world was considered interesting because of its wide mobility, but the lack of precision made it frustrating to use. User 4 felt that the moving blocks

Drag World	Ease of Use	Immersiveness	Comfort
User 1	3	2	1
User 2	4	3	3
User 3	3	3.5	4
User 4	5	3	2
User 5	3	3	3
User 6	3.5	2	2.5
User 7	3	4	4
User 8	2	3	3
User 9	4	3	2.5
User 10	2	2	3

Table 5.6: Score results for drag world.

were too easy to dodge, as large arm movements allowed for very swift movements. Figure 5.5 shows how much the users spent time in different environments with drag world.

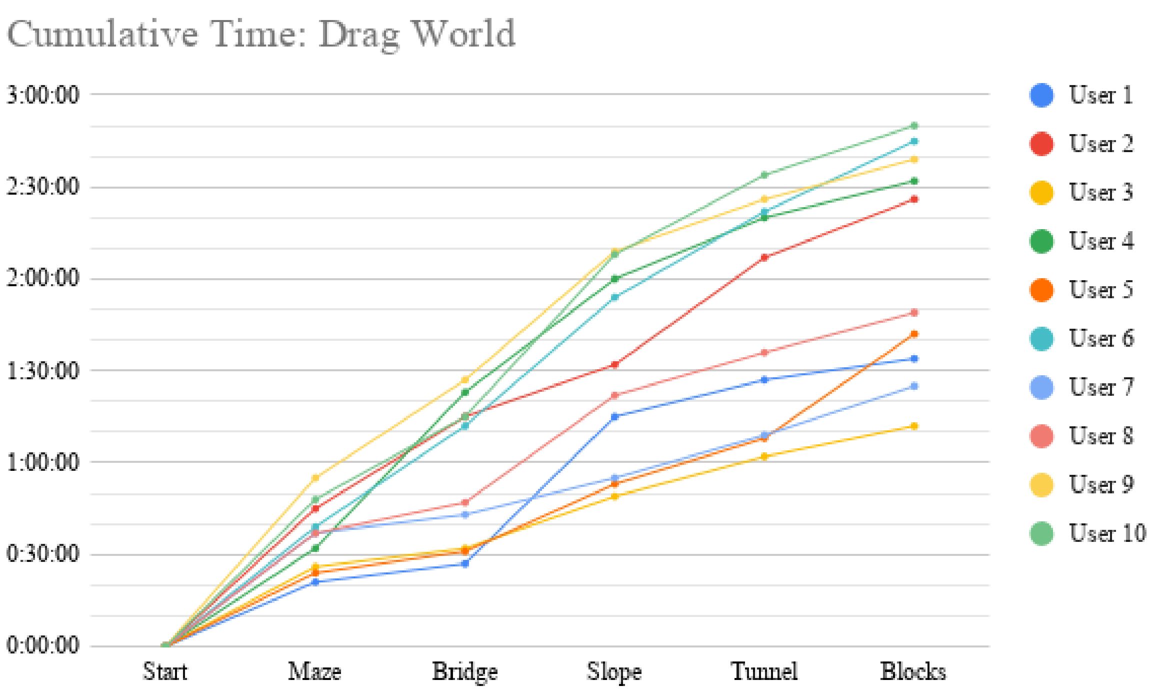

Figure 5.5: Cumulative time for each user with the Drag World locomotion method.

Arm Swinger	Ease of Use	Immersiveness	Comfort
User 1	4	5	1
User 2	4	4	4
User 3	4	4.5	4
User 4	5	4	3
User 5	4	4.5	4.5
User 6	3.5	3.5	3
User 7	2	3	3
User 8	3	4	3
User 9	3	3.5	2.5
User 10	3.5	5	3

Table 5.7: Score results for arm swinger.

5.2.6 Arm swinger

The arm swinger locomotion method was chosen as the best one by more users than any other locomotion method. The users generally considered it very immersive, as the movement required physical actions. However, for many users, it took quite a long to get used to. User 5 commended its versatility in both fast movement and precise movements. Two users, 6 and 9, commented on the way the locomotion method decided the user's movement direction – average direction vector of both controllers – by describing it challenging to use. Rest of the users did not comment on this at all, while providing high ratings for ease of use. The results for this locomotion method can be seen in Table 5.7. Figure 5.6 shows how much the users spent time in different environments with arm swinger.

Five users noted the locomotion method's immersiveness, how it provided a strong feeling of being in the game world. User 6, however, said it felt unnatural. Two users, 1 and 10, noted that the locomotion method was uncomfortable to use in small spaces, as they would easily hit the walls because of moving too fast.

The action sequences were described as interesting by eight users. User 10 commented that with this locomotion method, all movement contains many interesting decisions to make. User 8 commented that during intense situations, they did not feel in control of their own movements due to often accidentally activating the locomotion.

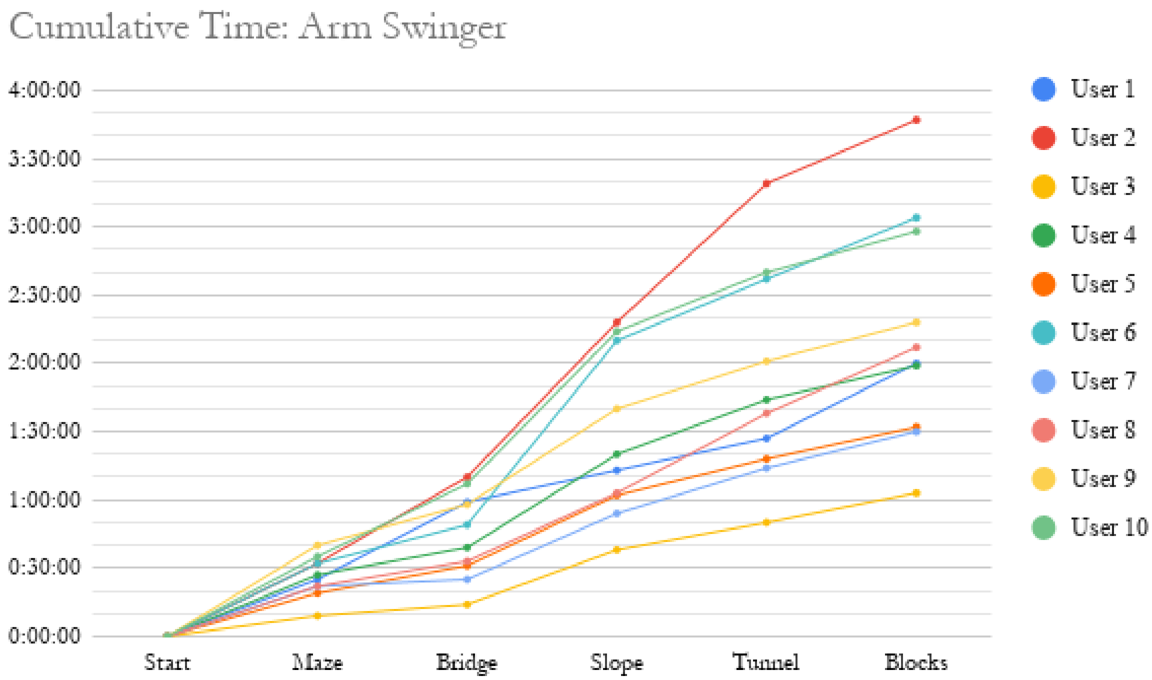

Figure 5.6: Cumulative time for each user with the Arm Swinger locomotion method.

5.2.7 Step multiplier

The step multiplier locomotion method gained the lowest overall scores in ease of use and immersiveness, as seen in Table 5.8. In comfort, however, it reached above-average scores, but was described as sometimes feeling dangerous, as the users had to be constantly aware of the limits of the physical space. This decreased their feeling of immersion.

Two users, 2 and 8 described the step multiplier locomotion as very immersive, with a caveat; as the immersion was broken as soon as the user reached the edge of the physical space. Three other users, 1, 3 and 5, felt the locomotion method was not immersive at all, as they had to be constantly aware of the physical space's walls to avoid bumping into them.

Two users, 7 and 9, commented on how it was very tedious to use when moving long distances. Three users commented on how they did not like at all the interruption caused by reaching the physical walls, and the readjustment of the user's position afterwards.

This locomotion method caused the most users to improvise their own ways to improve it. User 4 noticed how their own voice bounced off the room's walls, and used this "echolocation" to estimate the distance to the wall in front of them. Another one, user 3, did not

Step Multiplier	Ease of Use	Immersiveness	Comfort
User 1	1	1	1
User 2	3	2	3
User 3	1.5	1.5	1
User 4	3	2	4
User 5	2	1.5	4
User 6	1.5	2	3
User 7	2	2	4
User 8	1	2	4
User 9	4	2	4
User 10	3	2	3.5

Table 5.8: Score results for step multiplier.

walk in the space at all, but rather just bent their upper body forward while turning on the movement speed amplification; this allowed them to move with a good pace without needing to walk physically at all.

The action sequences were considered very bad, as the users felt uncomfortable doing fast and sudden movements with the risk of hitting a wall. The amount of sideways movement for the movement augmentation was also widely considered to feel bad. Because of the challenge posed by this, only user 4 managed to cross the bridge without falling. The movement speed multiplier was applied in the test environment to both forwards and sideways movement; if this is used in a VR application, we recommend that the speed multiplier should not apply for sideways movement at all, or is increased linearly as the user's speed increases without a speed threshold. Applying the movement speed amplification only to forwards movement was also recommended in the Seven League Boots paper by Interrante et al. [40], but this feature was not implemented in VRTK [25].

Figure 5.7 shows how much the users spent time in different environments with step multiplier. Step multiplier was clearly the locomotion method that required the most time, as the users had to spend a lot of time readjusting their position within the room-scale space between each "spurt". The fastest user, user 1, spent 4 minutes and 33 seconds, and the slowest one, user 9, 8 minutes and 37 seconds. This was the longest time out of all playthroughs.

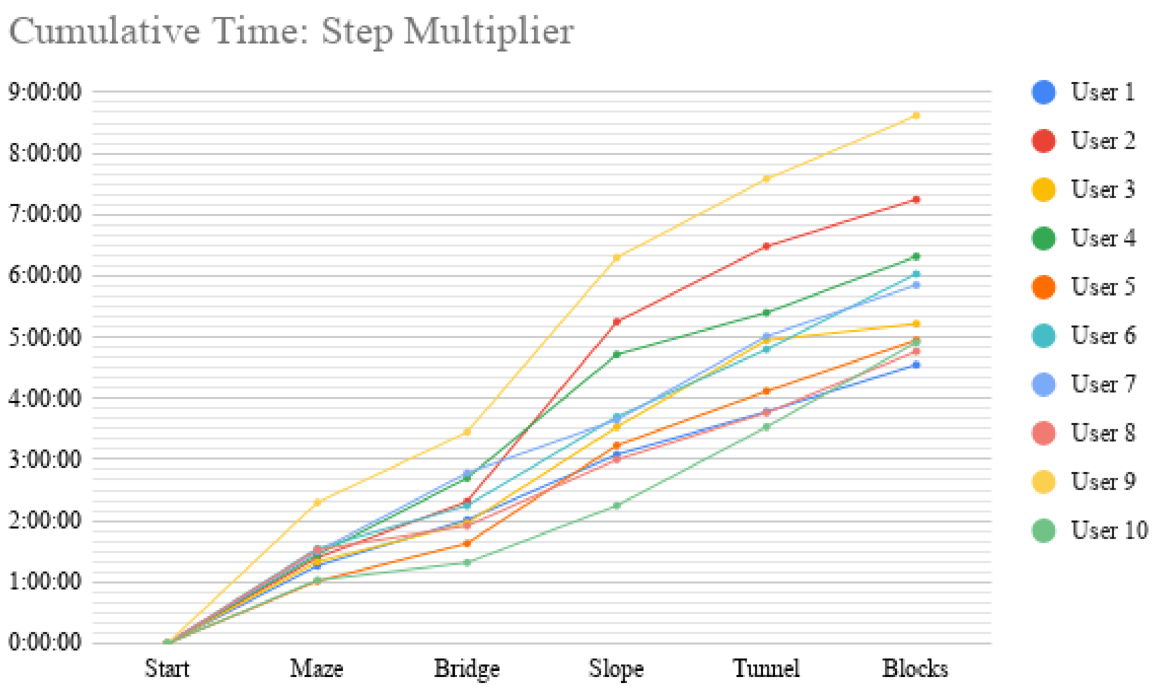

Figure 5.7: Cumulative time for each user with the Step Multiplier locomotion method.

5.3 Favourite locomotion methods

In Table 4.1 we can see what the users ended up considering their favourite locomotion mechanics when asked the question "which locomotion method would you pick for daily use". Four users were unable to decide between two. User 5 had a hard time choosing a favourite, and ended up not selecting one.

The teleportation locomotion methods were selected as their favourite by four users, with two selecting dash teleport and three preferring blink teleport. The touchpad methods were also well represented, with three users liking the regular version. User 7 became enamoured with the touchpad with rotation locomotion method because of its uniqueness.

The arm swinger locomotion was chosen as a favourite by five users, reaching the top in the ranking. It was praised for its high immersiveness and ease of use, which overshadowed the users' feelings of discomfort; notably, the user 9 gave arm swinger average score results and 2.5/5 in comfort after using it, but afterwards they decided they liked it a lot.

5.4 Observations on environments

In this section, we go through all of the environments and discuss the interview results for each one of them and each locomotion method. Some environments and locomotion methods gained more comments from the users than others, these comments are discussed in further detail in the upcoming subsections.

5.4.1 Maze

In general, the maze was considered to be easy to navigate with all locomotion methods, however some locomotion method caused loss of sense of direction. The blink teleportation method proved to be the most confusing in the maze environment. As the users could not see movement, three reported being confused by their new position after the movement. This was partly because of the locomotion itself not visualizing movement, and partly because the different corners of the narrow maze were not very distinguishable from one position to another. The effect of this was amplified by the wall surfaces having a repeating, uniform texture. This could be improved in game design; having environments unique and distinguishable from every angle instead of having repeating environments also improves the user's comfort with blink teleport locomotion.

Figure 5.8 shows how much time was spent in this environment for each locomotion method. This figure shows a pattern that is repeated also in all other enviroments; step multiplier is the major outlier, taking more than two times longer than the next locomotion method. In this scenario, dash teleport was the fastest locomotion method, followed by touchpad. Interestingly, blink teleport required more time than dash teleport. This visualizes the effect of the users losing their sense of position between each teleportation.

5.4.2 Bridge

The bridge section proved to be difficult for many users, especially with physical locomotion methods. Only a single user, 4, managed to cross the bridge with the step multiplier locomotion method, and only two, 4 and 8, with drag world. In this scenario, we counted how many users fell off the bridge with which locomotion methods. These can be seen in Table 5.9, which shows that the bridge was very difficult to cross with physical locomotion methods.

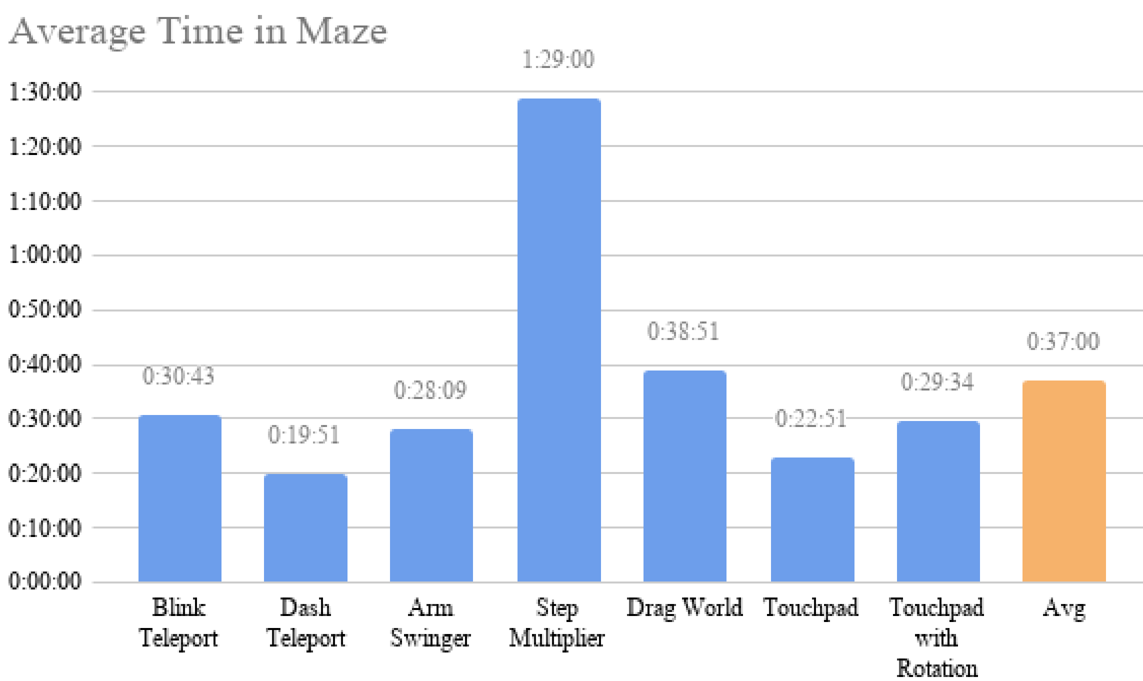

Figure 5.8: Average time spent in the maze environment for each locomotion method.

Teleportation locomotion made the bridge a mostly trivial challenge, even though the teleportation range required the users to make one stop on the bridge. This was because with teleportation-based locomotion methods it is more difficult for the user to do accidental movement that would drop them off the bridge. However, blink teleport

Similarly, the touchpad-based locomotion methods proved effective in crossing the bridge without any issues, although to a lesser extent. These locomotion methods allow the user to pick a movement vector and keep moving along that rail perfectly linearly, if they keep pressing the touchpad in the same position without moving their finger.

The bridge was considerably more difficult to cross with physical locomotion methods, because using them the users would easily input extra horizontal movement and possibly drop off the bridge as a result. The step multiplier locomotion method proved almost impossible to use effectively in this scenario, as the movement speed multiplier and the dead zone before movement activates created sharp and sudden horizontal movements, even though the dead zone was designed to prevent accidental movement. The drag world locomotion method was also difficult for users, only users 4 and 8 managed to cross the bridge using it, but it was widely considered exciting, as it allowed the users to do more precise movements compared to the other physical locomotion methods.

User ID vs locomotion method	1	2	3	4	5	6	7	8	9	10
Blink teleport						X		X		
Dash teleport										
Touchpad		X	X							
Touchpad with rotation		X								
Drag world	X	X	X		X	X	X		X	X
Arm swinger	X					X	X		X	X
Step multiplier	X	X	X		X	X	X	X	X	X

Table 5.9: A table of users and locomotion methods, showing how many users fell off the bridge while trying to cross it. X represents falling. Physical locomotion methods are heavily represented here.

Figure 5.9 shows how much time was spent in this environment for each locomotion method. It is important to note that the users were instructed to move to the next scenario if they fell off the bridge, so it does not truly represent the time it took to cross the bridge, and thus it is not possible to make meaningful conclusions from it. It is included here for the sake of completeness. Multiple users wished they could have spent more time practicing crossing the bridge after falling off it with the physical locomotion methods, which suggests that it presented an interesting challenge.

5.4.3 Slopes

The slopes were relatively easy to navigate for all users. Interestingly, most users picked the same route through the environment. This route, visualized in Figure 5.10, offered the path of least resistance because it contained the least ground height variations. Even though only a few users tested whether they could move up steep slopes, all users tended to avoid them.

With the non-continuous teleportation locomotion methods, utilizing the Bézier curve aiming allowing the users to scale steep slopes without effort, the paths chosen were generally more straightforward, though they tended to follow the same general route as with the continuous locomotion methods.

The average time spent in the maze for each locomotion method is shown in Figure 5.11. The artificial touchpad and teleportation locomotion methods were the fastest ones here, as the users spent more time considering their route with the physical locomotion methods.

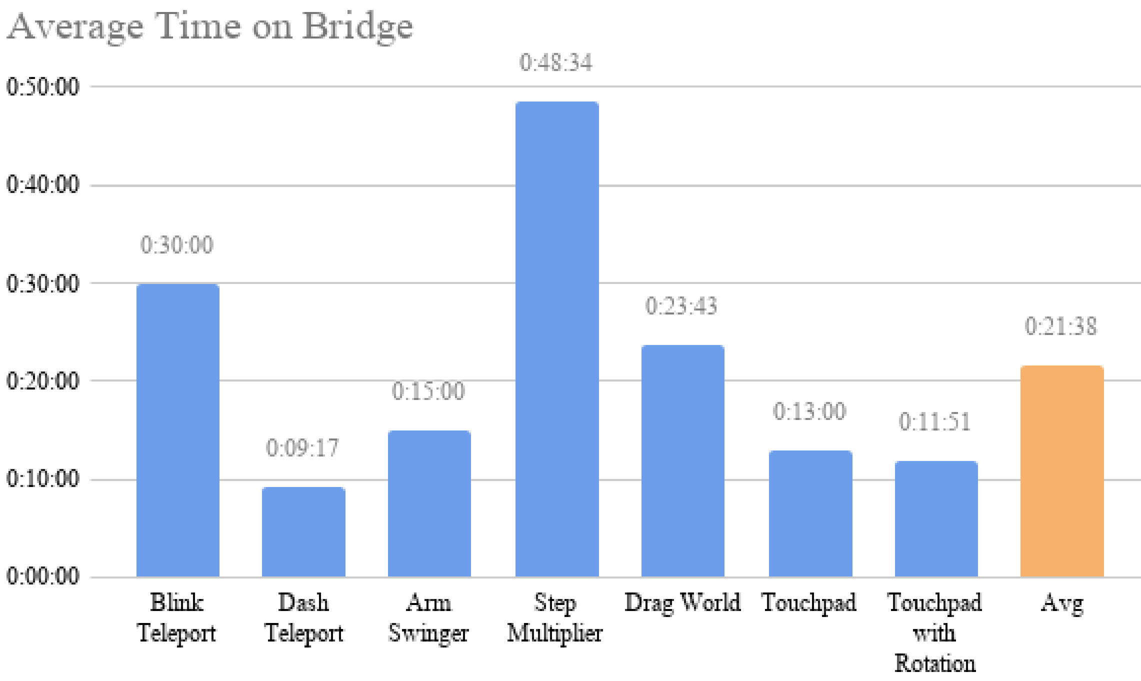

Figure 5.9: Average time spent in the bridge environment for each locomotion method.

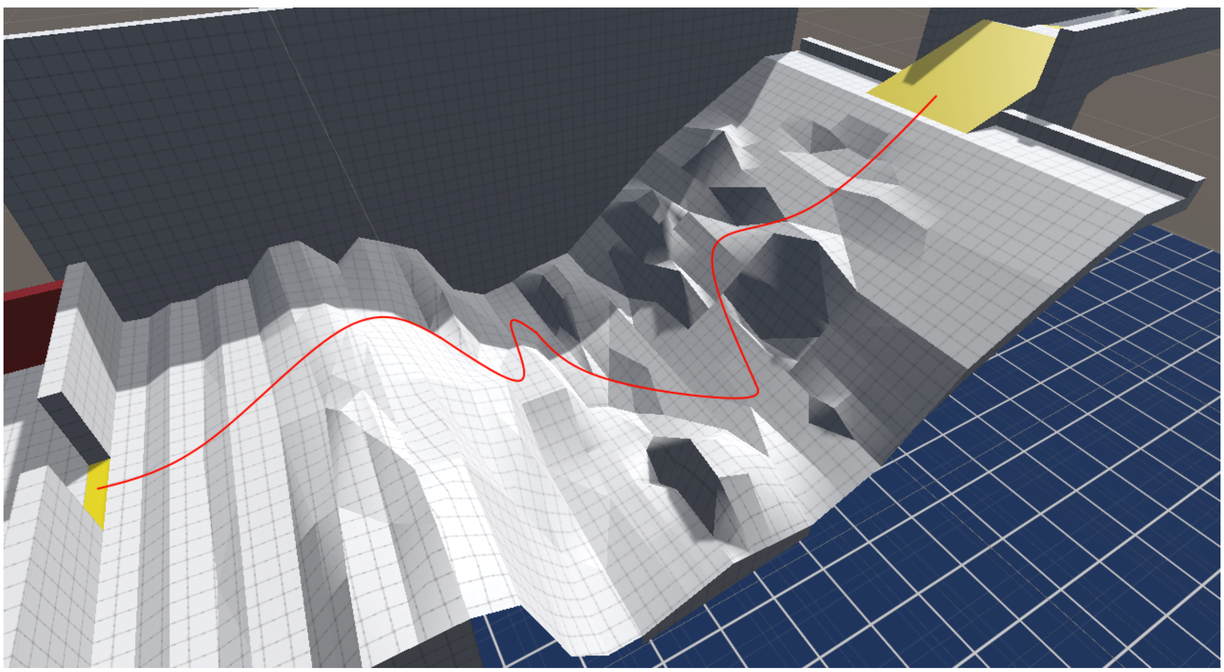

Figure 5.10: Most users selected a path of least resistance through the slopes scenario. Here is visualized the most common path taken; it is the route through the environment that contains the least altitude variations.

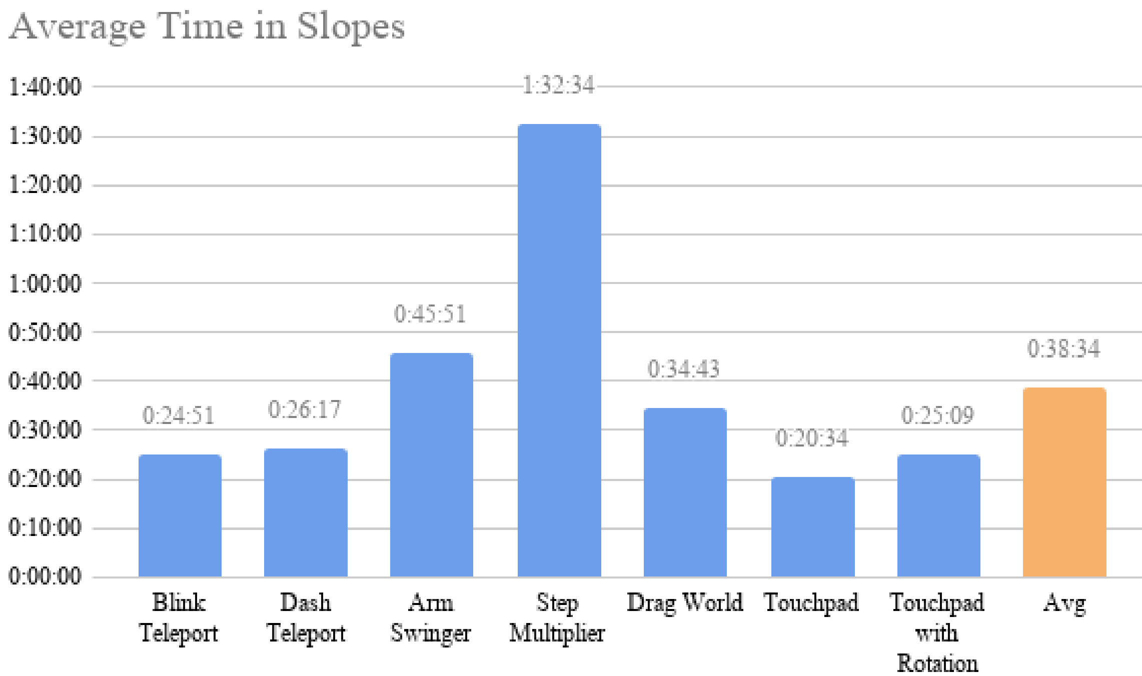

Figure 5.11: Average time spent in the slopes environment for each locomotion method.

5.4.4 Moving wall

The moving wall section was widely considered very exciting for physical locomotion methods. For artificial locomotion methods, where no effort was needed to move quickly, it was considered boring and effortless. When using teleportation-based locomotion methods, most users barely paid any attention to the wall, as the escape provided no challenge for them.

Touchpad-based locomotion methods, like teleportation-based ones, provided little excitement for the users, as they could simply keep pressing the input without doing any physical activity to escape the wall; movement like this was not able to create excitement, even though it was actual movement, rather than teleportation.

Physical locomotion methods were considered far more exciting. As the average movement speed was a lot slower with step multiplier compared to other locomotion methods, it was considered here very exciting by multiple users, as the scenario felt more intense with it.

Even though the movement speed of the wall was adjusted so that it slowed down as it approached the player, some users did not manage to move quickly enough to avoid it. These results are shown in Table 5.10. This shows a higher correlation between the user

User ID vs locomotion method	1	2	3	4	5	6	7	8	9	10
Blink teleport		X				X				
Dash teleport						X				
Touchpad										
Touchpad with rotation		X				X				
Drag world	X									
Arm swinger		X								
Step multiplier	X	X				X				

Table 5.10: This table shows which users were hit by the wall with different locomotion methods. Each collision is marked with an X.

and amount of collisions than between the locomotion method and amount of collisions, with both users 2 and 6 hitting the wall multiple times. Most users managed to avoid the wall completely.

Figure 5.12 shows how much time was spent in this environment for each locomotion method. The results are somewhat even for all locomotion results besides step multiplier, with the teleportation methods and touchpad locomotion reaching low average times.

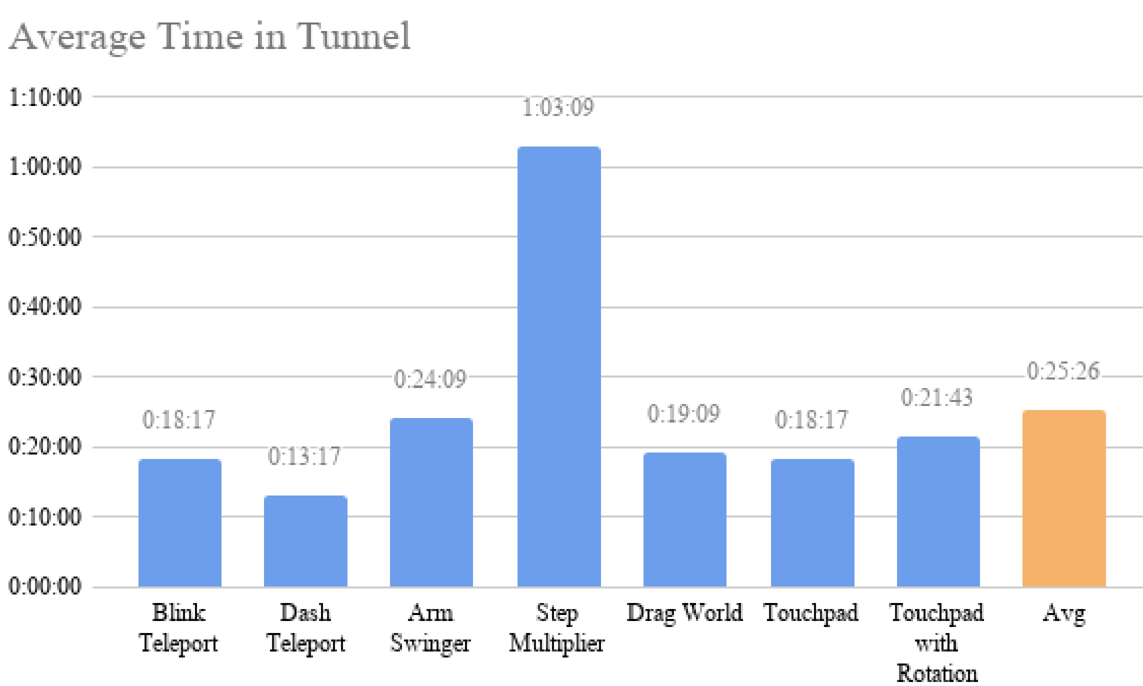

Figure 5.12: Average time spent in the moving wall environment for each locomotion method.

User ID vs locomotion method	1	2	3	4	5	6	7	8	9	10
Blink teleport		1			2	1				1
Dash teleport						2				1
Touchpad		2								
Touchpad with rotation			3							
Drag world		1							2	
Arm swinger			1	1		1				
Step multiplier	1	2		1	1	1	1			

Table 5.11: This table shows how many times users collided with the moving blocks with each locomotion method.

5.4.5 Moving blocks

The moving blocks were considered interesting and exciting with all physical locomotion methods and the artificial touchpad locomotion methods. With the teleportation locomotion methods, the moving blocks scenario was considered effortless and boring, and most users breezed through it, facing little difficulty. Multiple users spent barely any time in this scenario, as it was possible to jump through this room with a handful of quick teleportations.

However, the continuous locomotion methods, physical methods and the touchpad movement, provided much enjoyment here. Some users spent more time in the environment than they needed to in order to stay in the way of the blocks and then move out of the way at the last second, simply toying with the scenario. Room-scale movement was also utilized in a natural way by multiple users, as the room provided enough space for the users to physically move out of the way of the blocks.

Table 5.11 shows how the users collided with the blocks with different locomotion methods. 6 out of 10 users hit a block at least once with the step multiplier locomotion method. As seen in the time Figure 5.13, the step multiplier locomotion method was also the slowest one. The slow movement speed correlates here with the amount of collisions, showing that the blocks were difficult to dodge with it.

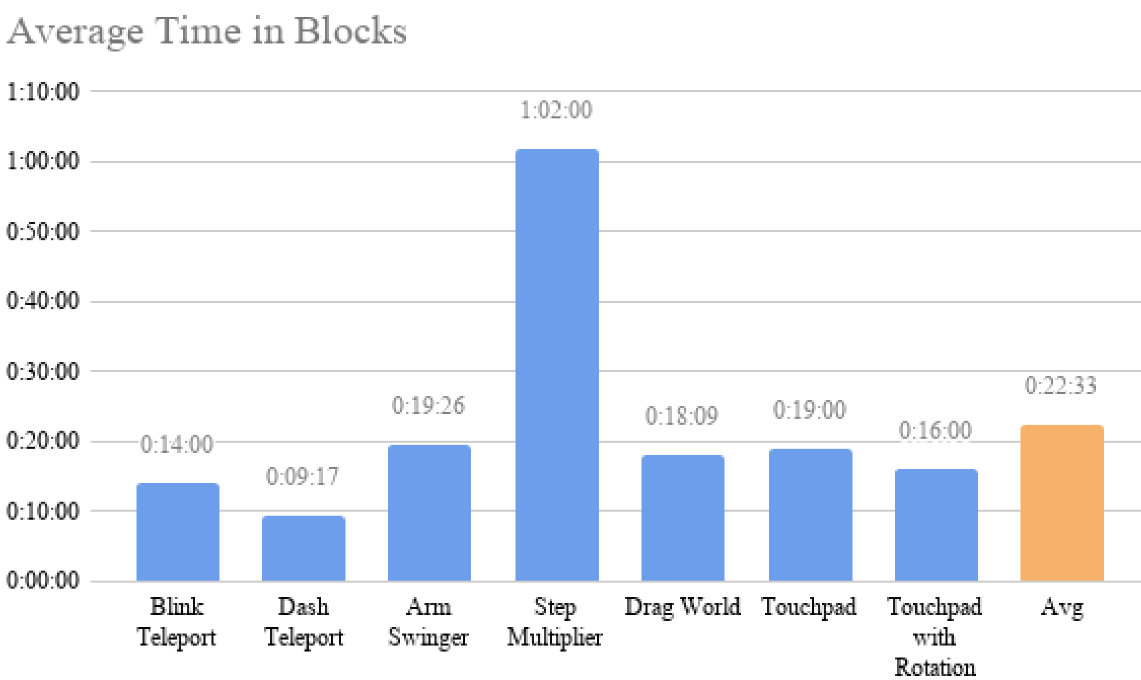

Figure 5.13: Average time spent in the moving blocks environment for each locomotion method.

6 Discussion

In this chapter, we discuss these results in a more general sense, aiming to provide concrete suggestions to what kind of locomotion methods are usable in different game situations, and what kind of game design solutions could be implemented to improve how different locomotion methods feel.

6.1 Analysis

From these results, we can conclude that there is a need for support for multiple locomotion methods in each game, as different people prefer different locomotion methods, and different game scenarios work differently based on what kind of locomotion is utilized. In general, artificial locomotion methods were better in the motion sickness aspect. Teleportation was suitable for everyone in terms of motion sickness, but in tight spaces it made some users lose their sense of position. This is important to take note of if the game environment contains repeating elements, and can possibly be remedied by the environment having many non-repeating, unique elements.

Additionally, all artificial locomotion methods reached a higher score in ease of use than any physical locomotion method. While many physical locomotion methods were considered intuitive, with arm swinger reaching the highest immersion score, the artificial locomotion methods required less effort to use effectively and were thus considered easy.

The immersiveness scores were mostly even across the field, with two notable outliers: arm swinger and step multiplier. From among the tested physical locomotion methods, arm swinger reached the highest score in immersion, shining in its ability to provide immersive movement with less motion sickness than its comparisons. It was also selected as favourite locomotion method by the most users, as seen in the user information table 4.1. However, it only gained a score of 3.1/5 in comfort, losing to all artificial locomotion methods except touchpad with rotation, which reached 3.05/5.

The step multiplier locomotion method received praise for its immersiveness, but it only reached an immersiveness score of 1.8/5. This was because the immersion broke as soon as the user encountered a wall. There have been attempts to improve this. For example, the redirected walking method proposed by Sun et al. utilizes an eye-tracking headset to subtly alter how the virtual environment is rendered on the headset's screen whenever the user's eyes make movements, making the user think they are walking straight forward while in reality they are walking in a circle [15].

Based on our results, the linear touchpad movement remains a somewhat safe locomotion method choice. It emulates classic video game movement well, and was considered very easy to use. As the movement was clearly visible to the users, they felt that touchpad movement was sufficiently immersive, even though it felt like static sliding at times. However, it caused much discomfort in some users, so it should not be the only available locomotion method.

Boletsis and Cedergren conducted a similar experiment by having 26 participants complete tasks in a virtual reality environment representing a city [13]. In their experiment, they gave each participant some time to practice the locomotion method before the tasks. Their locomotion methods were walk-in-place, where the user has a tracker mounted on their leg, controller/joystick which functions similarly to our touchpad locomotion, and blink teleport. Their scoring categories were also different; they utilized the Game Experience Questionnaire [42], which has considerably more evaluation criteria than our experiment.

Walking-in-place is somewhat comparable to arm swinger, but differing in that it uses an additional tracker; both locomotion methods utilize the user's body movement to initiate locomotion. Like arm swinger, it was considered highly immersive in Boletsis and Cedergren's experiment. They found that controller/joystick locomotion was considered easy to use, but gained moderate-to-high scores in immersiveness, and caused motion sickness for some users in the beginning. In our experiment the immersion score for touchpad locomotion was 3/5 for the regular version, which is a moderate score. We did not track how the user's comfort level with the locomotion changed during the experiment, but the end results in comfort ranged widely from 1 to 5, with 3 being the most common score. For blink teleportation, Boletsis and Cedergren found that it had moderate-to-high scores in ease of use, moderate performance in immersion and low motion sickness. In our experiment, it was considered very easy to use, garnered low immersiveness scores but was the most comfortable out of all. For the most part, the results of these two experiments were similar.

6.2 Proposal for locomotion implementation in a virtual reality game

If the virtual reality game does not require the user to use their movement as a gameplay mechanic, the teleportation locomotion methods are the best for accessibility and comfort. If immersion is not a concern, or the main game mechanics provide interesting gameplay outside the player's movement, these locomotion methods provide high usability.

However, if the game contains game mechanics where the user's movement itself is used as a game mechanic or it should be challenging to move in varying terrain, the teleportation locomotion methods cannot be used. In this case, we could utilize both artificial and physical locomotion methods; the artificial ones would be available as comfortable, easy-to-use options, and the physical ones would be aimed at more advanced users. In both of these categories, the locomotion methods would offer continuous movement, as it is the best in dynamic gameplay situations. The touchpad movement would be the best choice for an artificial locomotion method, as it is more immersive and almost as easy to use as teleportation locomotion. However, it has a higher potential for discomfort. From among the physical locomotion methods, arm swinger provides the easiest and most immersive movement, while still having a level of comfort higher than average. These locomotion methods were among the most well-liked by the users, as seen in the results of the favourite locomotion methods question.

As an accessibility feature, a game with movement-related game mechanics could still perhaps utilize teleportation locomotion, with some adjustments. For example, a pathfinding algorithm could be used to detect whether the location the user tries to teleport to is valid, in the sense that it could be also be reached with continuous movement locomotion methods. In our experiment, we also noted how it was possible for a teleportation locomotion user to move across environments very quickly, avoiding all challenge. To ensure that the user can use the teleportation locomotion method to move only at a comparable speed to users using continuous locomotion, the teleportation aiming curve's range could be decreased, and a cooldown timer implemented to increase time between teleportations.

However, utilizing pathfinding in detecting the teleportation locomotion method's valid target locations might introduce some problems in corner cases. For example, arm swinger and touchpad movement allow the user to drop off ledges, which is something that the teleportation locomotion does not directly allow, as the target location cannot be in midair. However, with room-scale locomotion the user can simply walk off the ledge, mostly eliminating this problem.

6.3 Validity

In this section, we discuss the experiment's validity from both internal and external perspectives [43].

6.3.1 Internal validity

From internal validity perspective, we should take note of the scoring system used in the user research. The scale was initially planned to be 1-5 without half points. However, the first user wanted to give half points in the very first question, so half points were then allowed for the entirety of the experiment. The wider scale produced more nuanced results from the users, even though integer scores were far more common than half points. This suggests that users were more inclined to give integer points and use half points only when they could not decide. This might have shifted the results a bit compared to if a proper 1-10 scale had been used. Utilizing a 1-10 scale from the beginning would thus have been a better choice.

Another aspect of internal validity to note is in the locomotion method implementation. The locomotion methods were manually adjusted versions of the ones found in VRTK; however, in some cases the tweaks could have been more optimized. For example, to match the speed of other locomotion methods, the multiplier of the step multiplier locomotion was increased from 2 to 6. This resulted in highly pronounced horizontal movement if the user moved their head horizontally, and the locomotion method would have been less disorienting if the step multiplication did not affect horizontal movement at all. The tweaks themselves that made the different locomotion methods match each other in terms of movement speed were also something that would have been interesting to run the experiment without. This, however, would have required even more time, and the movement speeds of the moving elements in the scenarios should also have been scaled accordingly, as it would have been impossible to avoid the moving wall with very slow locomotion. This would also have made the locomotion methods less comparable, as each of them would have been tested in an environment that behaved differently.

The virtual environments could also have been improved; for example, in the end it was not very useful to see if the users fell of the bridge or not; this happened very often. If the bridge was slightly wider, it would have provided a just as exciting challenge without ending so abruptly for so many users.

6.3.2 External validity

One notable caveat of this experiment is that the user group size was only 10 people. The group is not large enough to make meaningful generalizations; this thesis aims to provide useful suggestions, but cannot claim that the theories presented here can be generalized to all situations.

In addition, it should be noted that this group of users was more technologically skilled and had more experience in video games than the average person. However, virtual reality systems and games are still aimed at hobbyists and not the average person, so the user group matched the target demographic of commercial virtual reality systems well.

6.4 Potential further research

There has also been research on additional ways to reduce motion sickness and make the locomotion methods more comfortable. Some of these systems utilize hardware features that are not yet implemented in current mass-market virtual reality systems [44]. Others are purely software-based; for example, Google Earth VR utilizes a system where the user's field of view decreases whenever they are moving [45]. This approach has also been researched academically [46]. Fernandes and Feiner conclude that this system is possible to be utilized without a decrease in the user's immersion in the virtual environment.

This thesis also only considers a small set of locomotion methods and possible environments, as the experiment would have required considerably more time with more options. We exclude, for example, all locomotion methods that utilize additional trackers. Additionally, using the Game Experience Questionnaire as a basis for the survey could supply even more nuanced results [42], but that also would increase the experiment's scope and time requirement substantially.

7 Conclusion

In this thesis, we examined different locomotion methods for virtual reality environments in games. We conducted an experiment to gauge their suitability to different types on virtual reality environments, and discussed these results. We provided suggestions on how to improve game design to make locomotion more exciting and more comfortable for virtual reality users, improving the player experience.

The experiment results showed that teleportation-based locomotion methods reigned supreme in ease of use and comfort, but only reached average scores in immersiveness. The most immersive locomotion method was the physical arm swinger method. The physical locomotion methods step multiplier and drag world received low scores compared to others. Touchpad locomotion was considered to be easy to use, averagely immersive but not too comfortable.

For a virtual reality game where the user's movement is not a central component, we propose utilizing the teleportation locomotion methods, blink teleport and dash teleport. However, in a game where the user's movement matters, arm swinger and touchpad can be used, with the user being able to switch between them. They both provide all-around good performance, with arm swinger being very immersive and touchpad being easy to use. However, this sacrifices some user comfort and may cause motion sickness; therefore we suggest that a modified teleportation locomotion method could be implemented as an additional option. This teleportation method should be modified to provide similar movement speed to the locomotion methods providing continuous movement, and a pathfinding algorithm could be used to ensure it does not allow the user to reach unintended locations.

These results of our experiment provide useful guidelines on what kind of locomotion options should be included in virtual reality games, where the user's immersion is important or the user's movement itself is used as a gameplay mechanic. Accessibility is also important to always keep in mind when designing these games, as not all players are able to utilize all locomotion methods, especially physical ones.

In this thesis, we only utilized the features of currently available consumer virtual reality systems. However, in the future the field of virtual reality locomotion will achieve new tools in the next hardware generations, when features such as eye-tracking and leg-tracking become more commonplace. These features will once again break new ground for locomotion in virtual reality games.

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