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Evaluation of the Effect of Different Tracker-driven Direction Sources on Continuous Artificial Locomotion in VR

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ABSTRACT

In this research, we evaluated different direction sources with Continuous Artificial Locomotion (CAL) in Virtual Reality (VR). In CAL, the user moves continuously in a virtual environment (VE) by pressing direction buttons on the controllers. However, the direction of the movement in most cases is defined either by the headset, or by one of the controllers, which may feel unnatural. In this study, we propose two extra direction sources, one based on the direction of the user's hips, and another based on the direction of their feet. To implement these direction methods, we utilized trackers that were placed on these body parts. We evaluated the four methods in terms of performance, preference, motion sickness and presence. To evaluate, we designed and implemented a VE, and conducted a user study with 24 participants. The users had to fulfill three tasks with each method: to navigate in a zigzag environment, then to cross a corridor while counting some dots positioned on the walls of that corridor, and finally to complete a mini game by placing colored cubes in the desired area. Data were collected both quantitatively and qualitatively. The results of our study indicate that hip and feet methods are the optimal selection in terms of performance for executing different virtual tasks; that motion sickness is not affected by the different direction sources; and that the users preferred most the feet and headset methods.

SUBJECT AREA: Human Computer Interaction

KEYWORDS: Virtual Reality, Locomotion, Interaction devices

ΠΕΡΙΛΗΨΗ

Αυτή η διπλωματική εξετάζει τις επιρροές διαφορετικών πηγών κατεύθυνσης σε συνεχή κίνηση στην Εικονική Πραγματικότητα. Με αυτόν τον τρόπο κίνησης, ο χρήστης κινείται συνεχόμενα στον εικονικό χώρο πατώντας πλήκτρα κατεύθυνσης στο χειριστήριο. Η κατεύθυνση της κίνησης, συνήθως, προέρχεται είτε από τη στροφή του κεφαλιού (headset), είτε από τη στροφή ενός από τα χειριστήρια. Σε αυτή την έρευνα, προτείνουμε δύο νέες τεχνικές για τον προσδιορισμό της κατεύθυνσης, μια με βάση τη μέση των χρηστών, και μια άλλη με βάση τα πόδια. Για την καταγραφή της κατεύθυνσης για αυτές τις τεχνικές, χρησιμοποιήθηκαν ανιχνευτές (trackers) που τοποθετήθηκαν σε αυτά σημεία (π.χ. στη μέση, στις κνήμες των ποδιών). Οι μέθοδοι αυτοί αξιολογήθηκαν με βάση την απόδοση και την προτίμηση των χρηστών, τη δυσφορία που τους προκάλεσε, και την αίσθηση της παρουσίας (presence) που τους δημιούργησε. Για να τις αξιολογήσουμε, σχεδιάστηκε και υλοποιήθηκε ένα εικονικό περιβάλλον, στο οποίο οι χρήστες είχαν να εκτελέσουν τρεις εργασίες με την κάθε μέθοδο. Αρχικά να περιπλανηθούν σε ένα ζιγκ-ζαγκ περιβάλλον, μετά να διασχίσουν έναν διάδρομο μετρώντας κάποιες κουκκίδες στα τοιχώματα του, και τέλος να ολοκληρώσουν ένα παιχνίδι στο οποίο τοποθετούν χρωματιστούς κύβους στα κατάλληλα μέρη. Στο πείραμα συμμετείχαν 24 χρήστες, και τα αποτελέσματα έδειξαν ότι, όταν η κατεύθυνση προσδιορίζεται από την μέση ή τα πόδια, οι χρήστες είναι πιο αποδοτικοί στο να εκτελούν εικονικές εργασίες, ότι η δυσφορία που προκαλείται είναι ανεξάρτητη από το πού προέρχεται η κατεύθυνση, και ότι οι χρήστες προτίμησαν κυρίως τις μεθόδους του κεφαλιού και των ποδιών.

ΘΕΜΑΤΙΚΗ ΠΕΡΙΟΧΗ: Αλληλεπίδραση Ανθρώπου Υπολογιστή

ΛΕΞΕΙΣ ΚΛΕΙΔΙΑ: Εικονική Πραγματικότητα, Μετακίνηση, Συσκευές αλληλεπίδρασης

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PREFACE

This thesis describes the research that has been conducted as part of my Master studies at the Department of Informatics and Telecommunications, National and Kapodistrian University of Athens. The user study was conducted in the course of one week at the university campus, and I would like to thank my supervisor for providing her office for this purpose.

1. INTRODUCTION

This chapter contains an introduction for this thesis. It begins with a brief description of Continuous Artificial Locomotion (CAL) in Virtual Reality (VR) and the main research problem that we focus on. Then, it is followed by the motivation behind the selection of this topic, and it proceeds with the contributions of this study to the respective field of VR. Lastly, there is an outline of how the rest of the thesis is structured, presenting the contents of each chapter.

1.1 Research Problem

Locomotion is probably one of the most widely used interaction components in VR, since in most cases some kind of navigation is required. It can be defined as the way for users to move through virtual worlds. Providing the ability to comfortably navigate in a VE and maintain a high sense of presence is considered to be something of paramount importance for VR. A poorly designed locomotion technique (LT) may distract the user, reduce immersion and introduce motion sickness [12]. Consequently, in the past decades, researchers have been experimenting with numerous locomotion techniques [9], exploring their strengths and weaknesses and improving them constantly [22]. Physical locomotion techniques like Real Walking (RW), despite being the most natural [45] [58], cannot be scaled, due to the limited physical space. Thus, in order to navigate beyond those confines, researchers need to switch to Alternative Locomotion Techniques (ALTs). One of the most commonly used among them is Continuous Artificial Locomotion (CAL), also called smooth locomotion [50]. In this locomotion technique, the user moves through the space by pressing directional buttons, sticks or pads to continuously move the viewpoint in the chosen direction. That approach moves the user just like in a first person video game which is equivalent to the default navigation technique for non-VR 3D experiences. However, this technique is highly related to causing VR sickness. This sickness is similar to motion sickness that people may feel in a car, also known as simulation sickness or cyber-sickness. Motion sickness is induced by the mismatch in sensory information between the visual and other senses, and it can lead to a headache, blurred vision, dizziness, disorientation, or nausea [12].

Furthermore, one other issue with CAL techniques is the source of the direction that the user moves to. The majority of the existing literature about CAL techniques, mainly focuses on how to move the user and not on the direction of movement, which is defined as the user's “forward”. Most of the time, the moving direction is driven from the orientation of the Head Mounted Display (HMD) which in a virtual world represents the viewpoint of the user. Thus, the users will move where their head is looking at. That technique is usually called ”gaze-steering”[58]. Another approach is ”hand-steering”, in which the direction is driven from the orientation of one of the hand-held controllers. In this case, the user moves towards where the controller is pointing at. Both of those techniques do not require extra hardware, since these devices are already tracked by the tracking mechanism of the VR system. However, those approaches do not have a direct relation with the way humans move in real life. Movement in the physical world is decoupled from the direction your head and hands are pointing, so you can look around, and use your hands as you move. As a result, those approaches may contribute to the created motion sickness that the user may feel. Moreover, by overloading the headset and the controllers with navigation functionalities [63], is considered detrimental to performance [30], given that in most VR experiences, those devices are already used for other interactions and tasks. For example, in a virtual shooting game, the players may want to aim (look) and shoot in a direction different from the one they are moving to. With these approaches, it is not possible to perform that kind of action.

The existing literature about virtual locomotion is mainly focusing on comparing LTs between them. About the overloading of the hands and headset with navigation tasks, existing research has shown that hands-free locomotion methods offer higher presence than hands-busy methods [30] when it comes to CAL techniques. In another study, they found out that when the locomotion method was driven by the feet it was more enjoyable by the users[63], since feet are more involved in physical locomotion. In [6] they presented two novel interfaces for navigation (a dance pad and a chair based) and asked the users to execute some tasks having their hands free from locomotion functionalities. That experiment showed that the issues related to direction, using those navigation interfaces, created critical impact in the user experience and performance. Despite those studies that focus on decoupling the existing hardware from locomotion tasks, to our knowledge the effects about the definition of direction are quite limited in existing literature.

In this study, we set out to explore the effects different sources of direction can have on the user experience when CAL is being used in VR navigation. Apart from the two common sources of direction, head and hands, we also explore two additional sources for getting the direction of movement, one based on hip and one other based on feet. In the latter case, we propose a novel way to infer the direction of the user movement by the mean angle from both feet. To achieve that, besides the existing hardware, extra tracking devices are being utilized, in order to get orientation data. Then we evaluate the effects of those direction sources in CAL, in terms of users' performance, preference, motion sickness and presence. Therefore, the examined direction source are:

- **Headset-based**: The direction of movement is driven from the orientation of the headset.
- **Controller-based**: In this case, the orientation of the controller directs the movement.
- **Hip-based**: Locomotion is directed by the hip.
- **Feet-based**: The direction of movement is calculated by the orientation of the feet.

For this research, an immersive VE was created to conduct a user study. This VE served as the experimental ”canvas” to evaluate and compare the CAL technique with these different direction sources. The locomotion is enabled using CAL based on a joystick. In this case, the user moves continuously through the VE by pressing the directional buttons of the controller. During the experiment, users were asked to execute three tasks with each one of the four direction sources. These tasks are to move on a ZigZag area, to walk through a Corridor while counting some dots on the walls, and to complete a simple interactive Color Game. The users have to fulfill all the tasks with all direction sources. When they complete them with a method, they have to answer some questions immersed about the used method and then, they remove the headset in order to relax and to answer some other questions related with the motion sickness that they may feel.

The aforementioned tasks are designed to help evaluate the efficiency, effectiveness, and spatial awareness of the users with each method. Specifically, we measure the performance time each user completes each task. Furthermore, usability, motion sickness and

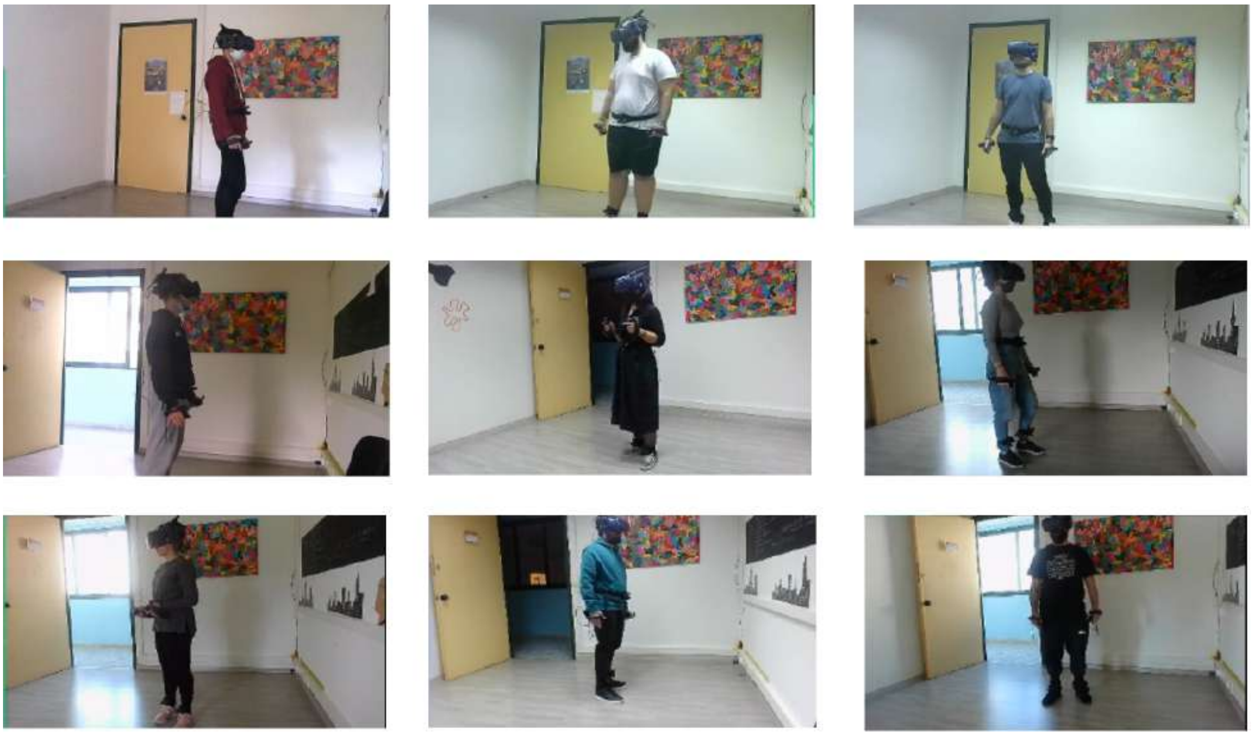


Figure 1.1: Some of the users that participated in our study.

presence, are assessed using a mixed methods approach of data collection through questionnaires and a concluding interview, at the end of each experiment. In this way, we aim to answer some experimental questions about the testing methods. These questions are:

- Which direction method would introduce less motion sickness?
- With which method the user performed best?
- Which method the user liked to use the most?
- Which method felt more real?

1.2 Motivation

In the last few years, VR has undergone a major hardware-driven revival, after a long period that has disappeared from the public. Nowadays, new devices are becoming available to the public, with relatively lower costs and with great performance. VR allows the users to extract themselves from the real environment into a VE, where they can observe, interact and even learn new skills. Therefore, it can create a great impact on the users. Hence, this revival of VR, not only has grabbed the interest of the public, but also that of many academic and industrial fields. It has opened new horizons in several areas such as robotics, urban planning, industry, art and education. Specifically, in the field of education, it has shown great potential in training. It can provide a remarkably effective teaching and learning environment, not only for school students[47], but also for architecture students[3] to even medical groups[28]. Moreover, VR is able to impact the psychology of the users [55], to even apply treatment therapies for relieving pain in physically impaired conditions [44].

In this way, VR applications and games have gained attention and popularity. According to a recent article published in RoadToVR, the number of VR headsets has reached a new record high of almost 3 million users [38]. The data used for their analysis were gathered during the period of the last five years from the monthly reports of Steam, the biggest digital distribution platform for video games in the world (Figure 1.2). This breakout is largely due to the introduction of new HMDs such as Oculus Rift™ [1] and HTC Vive™[2], which can provide six degrees of freedom (6DOF) and room scale tracking.

A common VR setup consists of: a head mounted display (HMD), two handheld controllers, and a tracking mechanism. The HMD provides stereoscopic viewing. The tracking mechanism provides the positional tracking of the devices. To accomplish that, most of the time extra hardware is being utilized (for example: base stations and lighthouses). Additionally, a high-end computer is needed to experience VR, which leads to increased cost, as a result discourages lots of new users. Consequently, this issue created the need for stand-alone VR solutions, that they could be simpler to install and use, since they don't need to be connected with an external computer. In this way, a stand-alone VR system can be more affordable to the public. For that reasons, the "biggest" players, namely HTC Vive and Oculus, have released stand-alone solutions (Quest[3] and Vive Focus[4]). Those VR systems are a revolutionary achievement, because not only do they not require a high-end computer in order to provide a high level virtual experience, but also they can provide positional tracking without utilizing extra hardware. Therefore, these systems are self-contained and can enable full tetherless mobility, with a lower cost [52]. In this way, VR companies have achieved to attract users, and to establish VR technologies in the commercial market. Already, the stand alone solution of Oculus (Quest 2), has become the leading headset used among the VR community [37], according to the monthly reports of steam. Furthermore, recently VR has gained even more popularity, with the mass recognition of Metaverse. Metaverse is a VE in which the users will be able not only to play together, but also to work, hang out and to even attend to concepts. In this way the VR technologies have gotten a lot of attention.

Furthermore, today, VR technologies can even provide full body tracking by utilizing tracking devices. In this way, all the user's movement can be transferred in the VR, leading to increased interactivity and immersion. Despite the fact that full body tracking isn't yet massively adopted, in the future it will be an important part of interactivity in VR and a crucial feature offered by VR hardware companies. Already more affordable trackers appear on the market (e.g. tundra trackers, etc.), and unofficial leaks have shown that Meta will provide a full body tracking solution in the near future. So it is safe to assume that full body tracking will be the norm, making the early exploration and exploitation of it for navigation a very important endeavor.

For VR to achieve mass adoption of the public, it should overcome some critical barriers. One of them is locomotion, which is strongly related to inducing motion sickness to users. VR communities have to find out how to provide the ability to navigate in VE, beyond the confines of available tracking space while minimizing motion sickness, and maintaining a high sense of presence. In this direction, this study aims to explore the effects that different direction sources can have on user experience with CAL. We are also taking advantage of new tetherless VR systems that allow us to expose the users to numerous turns and rotations

[1] https://www.oculus.com/

[2] https://www.vive.com/eu/

[3] https://www.oculus.com/quest-2/

[4] https://www.visartech.com/blog/htc-vive-focus-review

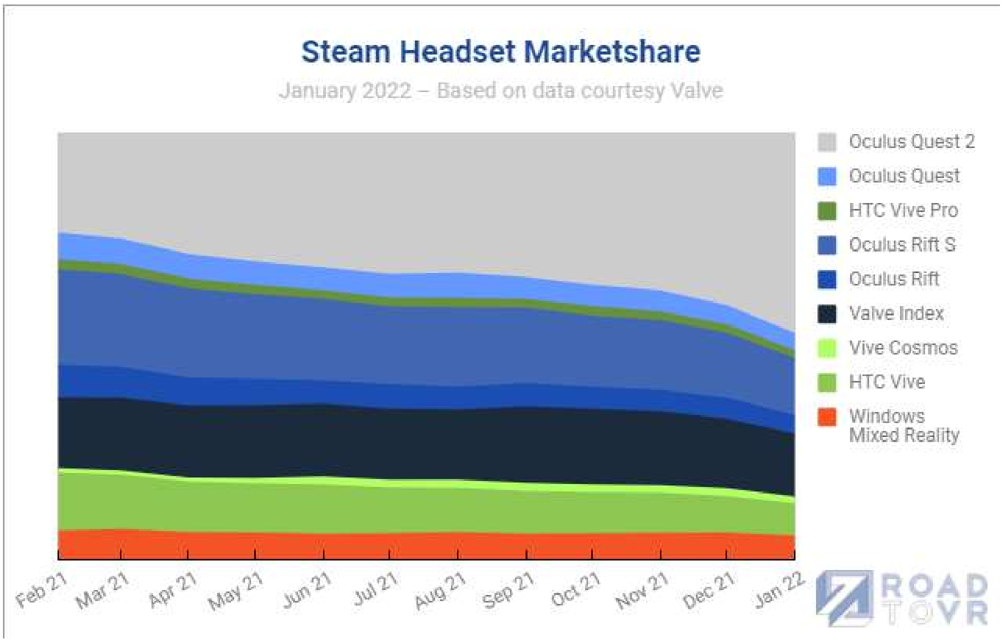


Figure 1.2: Share of VR Headsets on Steam. [38]

In addition, the hip-based direction source, that this study examines, appears to be a well known technique between the VR community. The Hip Locomotion, as the community refers to it, can be easily implemented by utilizing some additional hardware on the area of the hip. This hardware has to be able to calculate its orientation, and to forward it to the VR headset. In this way, multiple mobile applications have been created in order to unlock this technique for the public. The most popular are the DecaMove[5] and the OwoTrack[6]. However, despite the fact that this direction source is promising and liked by the VR community, there is no research that evaluates and compares it with the other well-known direction sources. On the other hand, feet-based direction source is more complex since it requires two tracking devices to acquire their orientation. Thus, it is not so easily reproduced, but still we believe that since the locomotion in the physical world is enabled by the feet, the users will feel more comfortable, and they will enjoy using them for directing the movement.

1.3 Contribution

As it is already mentioned, researchers have come up with numerous LTs, in the past decades. Those techniques are constantly being compared with one another and improved, in order for the user to be able to navigate more comfortably. The goal is to increase the sense of presence and reduce the generated motion sickness. CAL is one such technique, providing a promising and widely used solution for navigating without losing spatial awareness[51]. Although previous research focuses on "how to move", the direction of movement hasn't been explored much. In most cases, the direction is driven either from the orientation of the HMD or from one of the controllers. However, these devices, in most of the VR applications, are already used for other interactions and tasks. Thus, not only this behavior can be unnatural, but also, it may overload these devices with navigation functionalities, impacting usability and user performance. In this study, we examine two

[5] https://play.google.com/store/apps/details?id=net.deca.decamove.android&hl=el&gl=US
[6] https://play.google.com/store/apps/details?id=org.ovrgyrotrackersync&hl=el&gl=US

extra direction sources, one using a body-centric technique, specifically the hip and another proposed approach based on the angles of the feet. We achieve that by utilizing multiple trackers placed on the body of the user, leveraging full-body tracking. Therefore, we aim to evaluate the effects of these different direction sources for the CAL, in terms of users' performance, preference, motion sickness and presence. Thus, our contribution more specifically aims to better understand the effects each direction source can have to the users, and more specifically when we remove the navigation functionalities from the controllers and the HMD. Furthermore, we contribute, through an experimental user study and appropriate evaluation, towards a proposed use of the possible direction sources that can be unlocked by utilizing full-body tracking, which may become the industry standard in the next few years.

Additionally, in regards to the hip-based technique, as it was already mentioned, this technique is already known in the VR community. However, it has not been studied yet by the research community. Thus, we want to evaluate this technique in terms of user preference, performance and feeling of motion sickness. Last but not least, we want to examine how the users will respond in a feet-based technique, since feet haven't been explored as input for the direction in CAL, but just like in real life, movement is performed by the feet.

With this work, we hope to contribute to the field of locomotion in VR by identifying the advantages and shortcomings of different locomotion methods, primarily in regard to improving the user's experience in the virtual environment.

1.4 Thesis structure

The structure of this Thesis starts with a presentation of the Background of the VR technologies and the Locomotion Techniques, and then follows the Environment Design of the experiment that we conducted in order to evaluate our methods. After that, is the Implementation and the Study that took place in order to create an efficient experiment. Lastly, we present the Analysis that we made with the collected data from the experiment, and an extra Discussion about the results, the limitations that we face and the future work.

2. BACKGROUND

2.1 Virtual Reality

Virtual Reality is a scientific field that studies the construction of synthetic interactive environments and the immersion of users in them through the utilization of specialized hardware and software [79]. One can easily notice that the title of the area itself is contradictory. Since what we call reality, the physical world that we perceive with our senses, is one, how can it be virtual? After all, the adjective ”virtual” means something fake or imaginary; certainly not real. The truth is that while there is this inherent contradiction in the name, the words manage to condense the real goal: to create artificial environments that are presented so convincingly to the user that they are perceived almost as ”reality”. Unlike traditional user interfaces, VR places users inside a VE, and instead of viewing a screen in front of them, users are immersed and able to interact with 3D worlds. By simulating as many senses as possible, such as vision, hearing, touch, and even smell, the computer is transformed into a gateway to this artificial world.

2.1.1 Development of VR Headsets

The first concept of a VR headset appeared in 1935, when science fiction author Stanley Weinbaum wrote Pygmalion’s Spectacles (Figure 2.1). This fictional short story presents a comprehensive and specific fictional model for virtual reality. In the story, the main character meets a professor who invents a pair of goggles that allow him to view a movie with sight, sound, taste, smell, and touch. In addition, he was even able to interact with the movie’s characters. The author’s career in science fiction was very short, due to his early death, but influential.

Figure 2.1: Pygmalion’s Spectacles is a science fiction story by Stanley G. Weinbaum (1935). [31]

In 1956, Morton Heilig, a filmmaker in the Hollywood motion picture industry, wanted to make people feel like they were ”in” the movie, so he invented Sensorama (Figure 2.2)[70]. Sensorama was a mechanical device that offered viewers an interactive experience. This machine was able to create a real city environment where people rode through on a motorcycle, and it was considered to be one of the first milestones in VR technologies. Heilig also patented the first example of a head-mounted display (HMD) device, called the Telesphere Mask (Figure 2.3), in 1960. It was a non-interactive film medium, without any motion tracking, that provided stereoscopic 3D and wide vision with stereo sound [1]. Many inventors would build upon his foundational work.

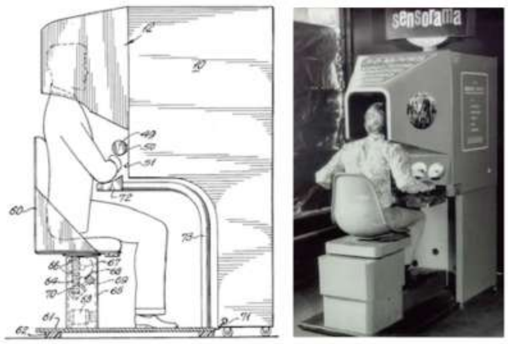


Figure 2.2: Sensorama: a machine that is one of the earliest known examples of immersive technology [70].

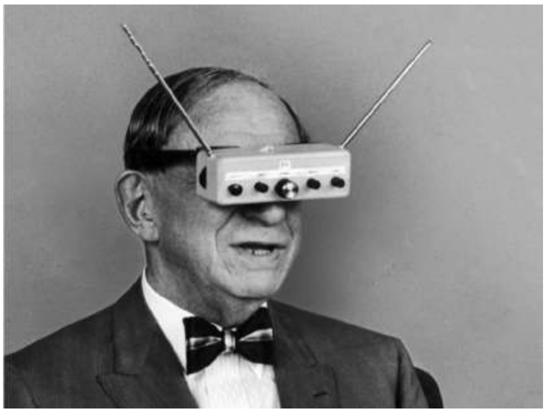


Figure 2.3: Telephere Mask: created in 1960 by Heilig [1].

The first motion tracking HMD was developed in 1961 by two Philco Corporation engineers (Comeau and Bryan), and was called the Headsight (Figure 2.4). It was not actually developed for virtual reality applications, but to allow immersive remote viewing of dangerous situations by the military. It was primarily used to move a remote camera, allowing a user to look around an environment without physically being there [1]. The first official HMD was created in 1968 by an inventor named Ivan Sutherland, and it was called ”The Sword of Damocles” (Figure 2.5) [72]. He suggested that it would serve as a window into the virtual world. It was also the first HMD that worked with computer hardware to create the virtual world and maintain it in real-time. It was so heavy that it was attached to the ceiling. Although the generated graphics were very simple, limited by the computing power available at the time.

However, the term VR was unknown by that time, until Jaron Lanier coined it many years later. Lanier is an American computer scientist and artist, who was born in 1960, and was the founder of one of the first companies to sell VR goggles and wired gloves. In this way, he is considered one of the founders of the field of VR.

The period from the 70s to the 90s was the period that personal computers and home consoles started to become available to the mass market. That led to VR research taking off with major advancements in VR hardware. Optical advances ran parallel to projects that worked on haptic devices and other instruments that would allow you to move around in virtual space. For example, NASA Ames Research Center in the mid-1980s developed the Virtual Interface Environment Workstation (VIEW) system (Figure 2.6)[46], combined with a head-mounted device with gloves to enable the haptic interaction. The purpose of that project was to be a VR simulation for astronaut training. The Virtuality Group released a series of games and arcade machines bringing VR to the public. Players wore a set of VR goggles and played on gaming machines with real-time (less than 50ms latency) immersive stereoscopic 3D visuals, just like those in Figure 2.7 [1]. Some units were also networked together for a multiplayer gaming experience. In addition, the first VR systems, with the ability to display 3D graphics, came to the market from Sega and Nintendo.

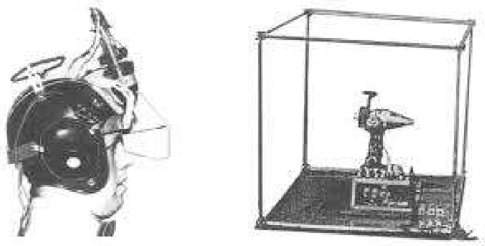


Figure 2.4: Headsight: the first motion-tracking device created in 1961 [14] .

Figure 2.5: The Sword of Damocles: The first HMD ever created[72].

Figure 2.6: NASA's VIEW [46].

Figure 2.7: Virtuality device [14].

Despite the fact that many companies tried to bring their HMD products to the market, the technology was not mature enough to support people's expectations. In those days computers were unable to process realistic graphics, the screen of the devices offered very low resolutions, low refresh rates, and was able to display only a few colors. In addition, very few cases had any tracking mechanism able to provide in the best case 3 Degrees of Freedom (3DOF), creating very low immersion along with motion sickness. Projection-based VR systems powered by supercomputers, such as the CAVE [**?**], offered immersive interactive multi-user experiences but were very expensive and thus limited to research laboratories.

That situation started to change in 2010, when Palmer Luckey designed a prototype for what would become the Oculus Rift virtual reality headset. That event triggered a new breakthrough for VR technologies. Many of the technical issues encountered in the 90s were resolved. The currently available chips of the market were able to provide satisfactory process power. Also, the rise of smartphones with touchscreens led to the creation of displays with high resolutions and refresh rates. These advancements created a fertile environment for VR technologies to rise again. In 2012, Palmer Luckey founded a company named Oculus and started a campaign with his latest prototype, which was called Rift. In 2014 Oculus was bought by Facebook and launched the first consumer version of Rift in 2016. In the same year, Valve and HTC, which had already announced their partnership, released their first version called HTC Vive. Many other big companies, seeing the potential of VR technologies, launched consumer products to fill the market gap. Google launched the Google Cardboard for mobile VR, Sony launched PSVR, and Samsung the Gear VR. However, the high-end VR market was led by Rift and HTC Vive.

Most of the VR systems depended on high-end computers or a console to function. That created the need for stand-alone VR systems that would be more accessible to the public at a lower cost since they would not require a computer. The big players were able to create their first stand-alone VR systems Figure 2.8, which have the ability to provide high resolutions and refresh rates, satisfactory graphics, and 6DOF while minimizing the hardware dependencies. In this way, they are able to provide high levels of immersion and usability. With these headsets, the VR market has reached over 3 million users. Nowadays, VR technologies are considered a growing industry, having new devices and new players joining the race and claiming a share of this market.

Figure 2.8: Stand-alone VR headsets.

In the next few years, VR technology is expected to grow further. Already, big companies are promising to help build the metaverse. The metaverse is a concept of a persistent, online, 3D universe that combines multiple different virtual spaces. Despite the existing VR which is mainly utilized in gaming, metaverse will allow users to work, meet, game, and socialize together in these 3D spaces. It is considered to be the evolution of the current social media, with some experts even believing it is the future iteration of the internet. It would connect multiple platforms, similar to the internet containing different websites accessible through a single browser, and it will be driven mainly by VR and Augmented Reality (AR) technologies. In this way, already many companies have announced new VR headsets that will be able to support the needs of metaverse. The concept of metaverse follows the idea of the Second Life which was launched in 2003 by Linden Lab and It was an online multimedia platform that allows people to create an avatar for themselves and have a second life in an online virtual world.

2.1.2 How modern VR works

Modern VR technologies are able to convince our brains that we are in a different place and transport us to any world we can imagine. This is achieved mainly based on the sense of sight, since humans are visual beings, but also, nowadays, through the sense of hearing, with the development of spatial 3D audio. That multi-sensory ability of current VR systems is capable enough to create an immersive experience, which some of them may make the users feel that they are actually there (to achieve presence [59]). This strong feeling is achieved by two main characteristics that a modern VR system provides.

The first one is the illusion of depth, which is accomplished with a technique called stereoscopy [71].. Stereoscopy is achieved by projecting two offset images separately to each eye. For example, the classic View-Master was based on this technique (Figure 2.9), which was first developed in 1939 and is still being used today. Moreover, similar techniques are also used in modern 3D movies in cinemas. In this way, the VR headsets show an almost identical image to each eye of the user with a small offset, creating the illusion of depth. This is similar to the way human eyes work.

Figure 2.9: classic View Master game.

The second important characteristic of a modern VR system is the real-time positional and rotational tracking [74]. That means that the movement of the user's head in the real world is translated into relative movement in the virtual world, having the visual graphics adapt respectively. To be convincing enough, it should be happening with latency so small that it is not noticeable to the human eye. In this way, there are no discrepancies between the movements of the head and the visual feedback, achieving higher immersion. In order to maximize that effect, the VR system should not only provide orientation tracking but also positional. Orientation tracking means that the device is able to track the three axes that it can rotate around (also known as pitch, yaw, and roll). When a device supports only that kind of tracking, we say that it provides 3DOF (Figure 2.10 at left). This can be accomplished with a set of sensors in the headset, like a gyroscope and accelerometer. Positional tracking, on the other hand, is the ability of the system to track its transformation in space, meaning its movement in the three directions that can be referred to as forward or backward, left or right, and up or down. For the systems that support both orientation and spatial tracking, we say that they provide 6DOF (Figure 2.10 at right). For providing that kind of tracking, a modern VR system utilizes a set of cameras combined with computer vision algorithms. The most common practices are outside-in tracking and inside-out tracking. In outside-in tracking, cameras are placed in stationary locations in the environment, and they detect some markers on top of the device, which are easily detectable.(Figure 2.11 at left). For example, Oculus Rift utilizes this technique, having as markers constellations of IR LEDs placed at the headset and controllers. By having multiple cameras, it is able to calculate their transformation accurately. In the case of inside-out tracking, cameras are placed on the device, and by observing the surrounding environment, it can calculate its movement. Markers can also be used in that technique, just like HTC Vive does, which in this case are the lighthouses that contain IR LEDs. However, it can be done also markerless just like the Oculus Quest 2, having the whole system self-contained where the spatial anchors for the positional calculations are set by detecting the stationary objects and landmarks (Figure 2.11 at right).

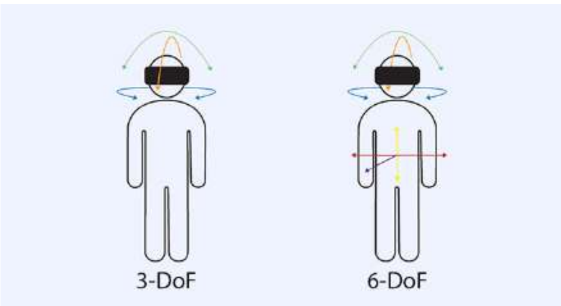


Figure 2.10: 3DOF and 6DOF [20].

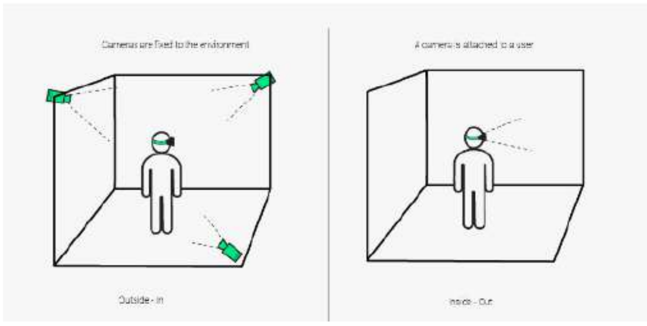


Figure 2.11: Outside-in and Inside-out tracking [20].

2.1.3 Controllers

A very important part of modern VR systems is the controllers. Through the controllers, users can bring their hands into the virtual world, and interact with the environment. Just like in the real world, in VR the hands are used to grab, throw, and move items. They also give access to interact with user interfaces. So, controllers are considered as the main gateway for interacting in virtual worlds. In current VR systems, there are two controllers, one for each hand of the user; in the virtual world they are frequently represented as virtual hands. The controllers, just like the headset, are being tracked with the VR system's tracking mechanism. So, they move in the virtual world, following the movements of the hands of the user in the real world. Moreover, in most of the controller designs, the buttons are placed in a way that, when the user presses them, the virtual hand (more specifically the fingers) illustrates a similar pose with the one in the real world (Figure 2.12). Some controllers, in order to create an even better representation of hands, are equipped with pressure sensors in some buttons. With those sensors, they can calculate and predict the position of the fingers, and visualize them more accurately in the VE. Some other VR systems are even able to support Hand Tracking, which is a technique that detects the position of hands and fingers[68]. This can be accomplished by either utilizing the cameras to detect the position of the hands, or by wearing special gloves that operate as controllers. With this method, users do not need to hold controllers, but they can interact with the VE with their own hands. However, these techniques are quite young, and have some weaknesses. Glove-based hand tracking can be cumbersome and difficult to use with different users and hand sizes[41]. Camera-based requires a lot of process power which may not be available, is not as smooth as controllers, and cannot work with occlusions. All those features aim to create a feeling of ownership of the virtual hands to the users, which leads to boosting the sense of presence in VEs.

Figure 2.12: On the left side is the controller of Oculus Quest and on the right side the projection of the virtual hand

Despite the buttons that provide one-dimensional information from the users' input, most of the controller designs contain a thumbstick or a touchpad. These input devices can provide two-dimensional information, so they can be used for controlling the movement in VR. This is achieved by maneuvering a lever on the controller with the thumb or by pressing over the touch-screen area on the touchpad.

2.1.4 Trackers

The rise of modern VR systems, created also the desire to go beyond the limited tracking of the head and hands, offering tracking capabilities of other parts of the body and even real life objects. This has the potential to generate a higher level of realism, enhancing interaction, immersion and presence. Trackers are little pucks that work in concert with VR headsets. In essence, they can track their spatial and orientational transformations, and transfer them to the VE. A common use case of trackers in VR applications is body-tracking. In this case, a tracker is placed somewhere on the user's body (like hip or feet). The number of tracked body parts in this use case can be scaled by utilizing multiple trackers to achieve full-body tracking. In that concept, multiple trackers are placed over the body of the user, making it possible to simulate the movement of the whole body in the VE Figure 2.14. Full-body tracking is considered to be the industry standard in the upcoming years, and it will enable many features for VR applications. Another common use case of the trackers is object-tracking, in which a tracker is placed over an object and its movement can be transferred into the virtual world. For example, in a VR application for tennis training, a real racket can be used by placing a tracker on it.

Already, more affordable trackers appear on the market, and unofficial leaks have shown that Meta will provide a full-body tracking solution soon. In this way, we can assume that full-body tracking will be the industry standard in the near future. Currently, the most popular trackers in the market are the Vive Trackers and the Tundra Truckers (Figure 2.13).In this study, Vive Trackers are used for obtaining the orientation of hip and feet.

Figure 2.13: Trackers.

Figure 2.14: Full body tracking using Vive Trackers [Manus] [49].

2.2 Motion Sickness

Locomotion in VR is strongly related with introducing motion sickness, which used to be one of the major concerns for the mass adoption of VR. This type of sickness is similar to the familiar motion sickness that people may feel while traveling on a vehicle, and it is also named as simulation sickness, cyber-sickness or VR sickness. It is induced from the mismatch in sensory information between the visual and other senses. In particular, in addition to vision and audio, movement in the real world affects also the proprioceptive and the vestibular senses, something that does not occur while the user moves just virtually. Therefore, when using LTs with continuous motion, users get conflicting movement cues from the proprioception and the vestibular sense compared to the ones they get from the sense of vision. Although the eyes perceive motion, the inner ear, which is sensitive to acceleration and orientation, does not perceive the same (or sometimes any) information, which is the major cause for motion sickness according to the sensory-conflict theory [40]. This discrepancy can lead to a headache, blurred vision, dizziness, disorientation, or nausea [5] and it can also affect the sense of presence in the VE [43]. There have been many studies on motion sickness in VR environments [23] and new technologies, which were not previously available, were applied to reduce motion sickness. For example, the resolution can be lowered or deliberately blurred, to reduce motion sickness [17]. The motion sickness effect is even higher in continuous locomotion, since it gives a better sense of continuity in the virtual world, leading to greater impacts. The challenge lies in finding a continuous locomotion technique that does not induce simulator sickness despite the stationary user. In two studies [64], [26], users initiated continuous movement in VR by pressing a button on the HTC Vive controller. The results of user studies showed that this induced significantly more simulator sickness than the use of non-continuous teleport with the same controller. In our study, motion sickness is one of the main axes for evaluating the different direction sources for CAL. Finding which direction source induces less motion sickness to the users is one of the goals of this research.

2.3 Presence

Presence is the feeling of being physically and spatially located in an environment [77]. Modern virtual reality's big breakthrough was the ability to achieve high levels of presence, transferring the users in the VE, making them believe that they are in another world other than where they are in reality [56]. So, VR allows the users to feel presence in another realm, in a virtual realm. Achieving higher levels of presence was a long and difficult process, but it's one of the features that makes modern VR magical. For VR to be compelling, your brain needs to accept the virtual world as real. According to Michael Abrash, who served as Chief Scientist in Oculus, in a talk that gave in 2014 while working at the VR research team of Valve [2], to establish Presence you need all the following:

- A wide field of view (80 degrees or better)
- Adequate resolution (1080p or better)
- Low pixel persistence (3 ms or less)
- A high enough refresh rate (>60 Hz, 95 Hz is enough but less may be adequate)

- Global display where all pixels are illuminated simultaneously (rolling display may work with eye tracking.)
- Optics (at most two lenses per eye with trade-offs, ideal optics not practical using current technology)
- Optical calibration
- Rock-solid tracking – translation with millimeter accuracy or better, orientation with quarter degree accuracy or better, and volume of 1.5 meter or more on a side
- Low latency (20 ms motion to last photon, 25 ms may be good enough)

Another way for VR to increase the sense of presence to users, is to simulate as many senses as possible [58] There's plenty of scope to enrich the sensory experience of VR. Better haptics and adding sensory input for smell and taste are some examples. Making headsets less obtrusive and offering a complete field of view is also high on the list of goals for VR development. VR finally offers an impressive sense of presence to the users, but many aspects of the technology are still at their infancy.

The sense of presence is also one of the main axes for evaluating our direction sources. The direction source that creates higher feelings of presence to the user can be assumed as the most "natural" since it creates the least distractions.

2.4 Locomotion

Locomotion is the act or ability of something to transport or move itself from place to place. It is directional movement that enables someone or something to move in physical space. The word derives from the Latin words locō (place) and mōtiō (to move). In human beings, the movements that result in a change of place or location are called locomotion. Walking, running, swimming, and jumping are different types of locomotion. This term is also used in ethology, and describes any of a variety of movements among animals that results in progression from one place to another.

In this section, Locomotion in VR is described, and some different LTs that have been developed in order to allow users to navigate in virtual worlds. Furthermore, the advantages and disadvantages of each technique are presented along with the reasons that led to the development of each one.

2.4.1 Virtual Locomotion

Virtual Locomotion is an important interaction component that enables navigation in VR environments. It is used to move the user's point of view in a Virtual Environment (VE) from one location to another. Therefore, it can be defined as self-propelled movement in a three-dimensional environment [36]. Locomotion is one of the most frequent interaction tasks in VR since in most cases users need to be moved in VE [12]. Except for the traveling part of locomotion in VEs, it is strongly related to the cognitive process [10] of wayfinding, and it is defined as the building and maintenance of a cognitive map, which is used to determine how to get from one location to another while moving [39]. A good locomotion technique (LT) should provide users with a friendly and comfortable way to navigate freely in the virtual environment, allowing them to explore it easily, maximizing immersion and the sense of presence. However, finding a suitable LT is considered something of paramount importance for VR, due to the strong influence on users [21]. A poorly designed LT may distract the user, reduce immersion and break presence. Also, some types of locomotion are considered to be the cause of motion sickness [12]. In traditional video games, movement mechanics mostly follow a standard control scheme, and it does not change from game to game a lot. That is not the case in VR. From the early days of VR, various LTs have been developed and studied [9]. One reason for that is the fact that the ability to track the VR headset in space, unlocks many possible control schemes for locomotion. Thus, virtual applications can select existing or design new LTs, depending on what suits them best and which one maximizes immersion. An efficient LT should not distract the users in order to avoid breaking presence, and also it should be available at an affordable cost. To group and sort all those numerous techniques that have been proposed for locomotion, a database has been created, which visualizes those techniques and connects them with similarity criteria [22] Figure 2.15. This database contains over 100 LTs, and it can be used for comparing them with each other.

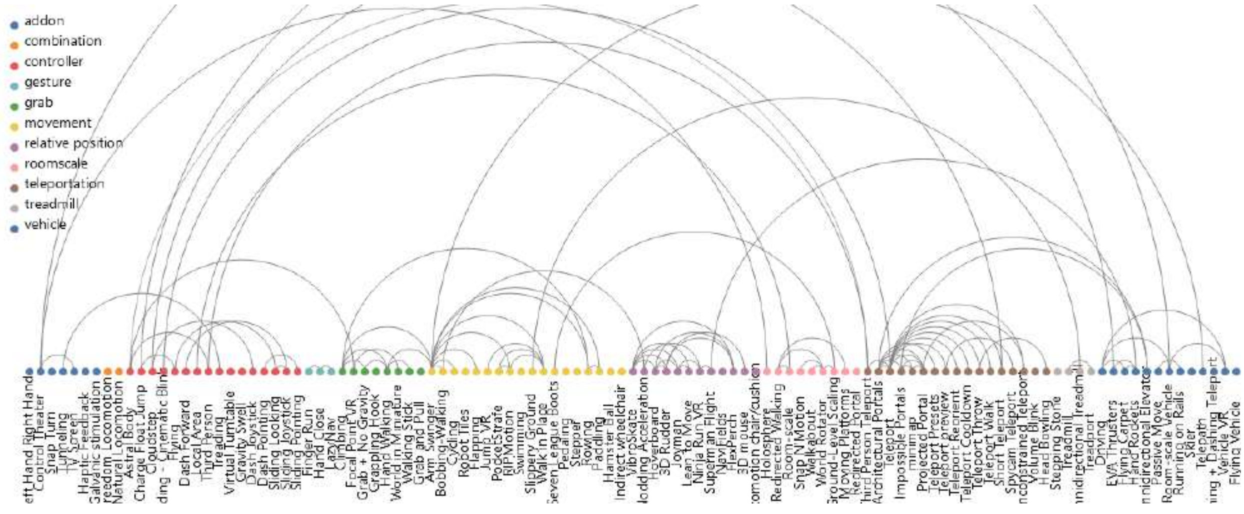


Figure 2.15: Locomotion Vault. the Extra Mile in Analyzing VR Locomotion Techniques[22].

In the rest of this section, the most frequent and important LTs are described along with related literature. For better organization, they are firstly grouped by their interaction type and then by their locomotion type in the VR. The interaction type of the LTs describes the way in which the user triggers VR navigation. Therefore, locomotion can be physical, i.e. exploiting physical motion cues for navigation and translating natural movement to VR motion through some kind of body tracking, or it can be artificial, i.e. utilizing input devices to direct VR motion and navigation [9]. Consequently, the documented VR LT were assigned to the classification categories, which are visualized in Figure 2.16

2.4.2 Physical

The LTs with physical interaction type are those that request the user to make some kind of physical movement that will then be translated as virtual movement in the VE [9]. The most well-known physical LT is **Real Walking (RW)**. In this technique, the users naturally walk freely in the tracked area, with their physical position and orientation mapped directly to the VE. To achieve that, the standard head tracking is being used to sense the movements of users, while they walk freely inside a tracked area. Then, that movement is exactly

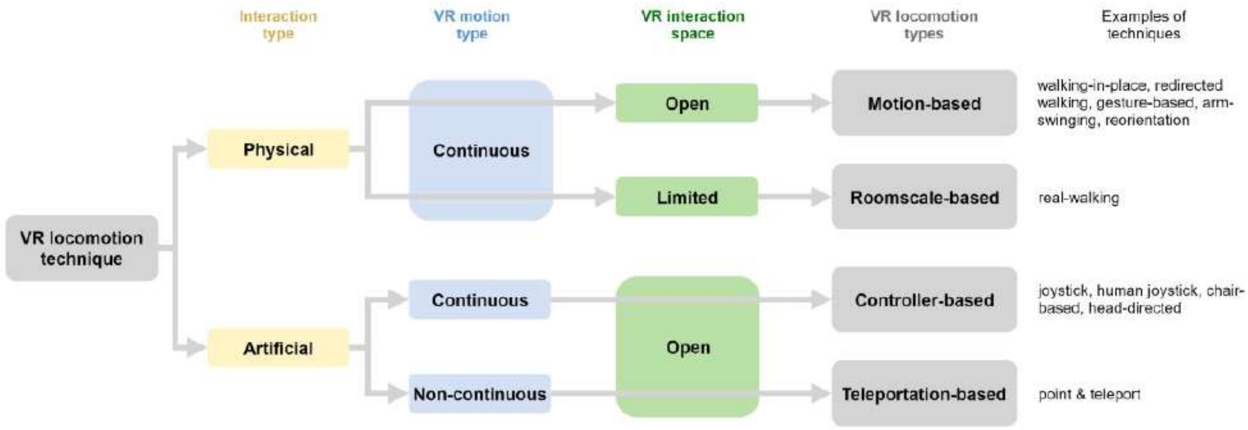


Figure 2.16: The VR locomotion typology [9].

mapped to the virtual world. It is considered to give great performance in navigation and wayfinding tasks [45] [57], as well as providing a high sense of presence to the users [48] and inducing less motion sickness [58]. However, large-scale VEs, like virtual cities for example, can not be traversed simply by normal walking. In practice, the tracked area is limited, so this technique cannot be applied to VEs larger than the available tracking area. Therefore, to overcome those issues, users have to switch to Alternative LTs (ALTs), which enable infinite navigation regardless of the size of the physical tracking space. Those techniques are typically activated using hand-held controllers and the tracked devices.

A common approach is called Redirect Walking (RDW). In this approach, algorithms keep the users inside the tracked area while they are walking. These algorithms can ensure safety for the users and provide unlimited natural walking. The main technique that is being used in RDW, is the Reorientation Technique (ROT). This technique either redirects the user away from the physical boundaries or the VE itself is being rotated to keep the users in a tracked area, without noticing it. For example, in [53] they present novel locomotion in which the users walk in a circular path and by applying directional changes, it is translated into a straight path in the VE (Figure 2.17). In this way, it allows the users to walk freely within a 3m x 3m tracked area. That study showed that this technique can enhance the feeling of presence and immersion without introducing a lot of motion sickness. In [48] proposed a large-scale RW interface in which the VE was rotated dynamically, using an efficient ROT, and having visual objects as distractors to prevent the user from leaving the tracked space. That method performed better compared with some artificial methods that are going to be described in the next sections. However, it increased the feeling of disorientation. Similarly, on [25], the user is reoriented using portals. The portals are placed automatically and guide the users in a safe position. This ROT technique did not cause any simulator sickness, but it had to interrupt the experience of the user in order to reset the user's position.

Other physical alternatives LTs that are being used are based on gestures. In these techniques, the user is staying in place, standing or steering, and performs a gesture, from either hands or legs. This gesture is being detected from the tracking mechanism and triggers virtual movement. Frequent gestures that are selected are, leaning [15], arm swinging [19] (Figure 2.18), tapping [34] and head bobbing [60]. These techniques show higher immersion when the gesture is related to the virtual experience, e.g. swimming, and due to the high mobility, it does not introduce high motion sickness[12]. Sometimes this LT is also called Human Joystick, since the users become the joystick that controls the movement. In [32] describes a method of physical leaning in order to explore a VE on a Nintendo Wii Fit Balance Board.

One of the most popular gesture-based ALTs is called Walking in Place (WIP). In this technique, the user marches without actually walking forward and this gesture triggers the locomotion in the virtual world. This technique resembles the RW approach, since it contains the walking motion, but it enables scaled navigation for large areas. Also, it offers a high presence and very low virtual sickness, since it is near-natural, and it decouples hands from navigation functionalities. A combination of WIP and RW was studied at [8], in which the users could walk naturally until they were close to the borders of the tracked area, where a grid-obstacle appeared, and the WIP technique was activated. This combination showed that it can offer a higher presence, and it was more interesting for the users.

In another approach to enable RW that will allow users to navigate in the VE by walking, without leaving the tracked area, many inventors and companies are trying to create a device that will attempt to simulate the walking motion of a person by using it. One of the first approaches is called Cybersphere [24]. Users enter a spherical system, and they can walk, run, jump or crawl in any direction while observing the VE. That device was mainly used for training simulations and civil engineering. Another approach is to create low friction surfaces, so that the users can walk freely, without any actual displacement. In this way, the first Omni-Directional Treadmill (ODT) [16] was created. Nowadays, the most advanced ODT in the market is the KatWalk, which appeared as a potential solution to the locomotion problem in VR. A modern ODT is shown at Figure 2.19. In [18], was evaluated the effects of this device in terms of efficiency, motion-sickness, presence, and fatigue. The results showed that this device was suitable for traveling in large VE. However, such devices have been criticized widely for their high cost, low usability and lagging responsiveness [45]. Another, more advanced approach to mimic the actual walking movement, are robotic solutions. The CircularFloor [78] consists of multiple robotic tiles, which the users can walk over. While the users are walking, these platforms behave as moving floors, keeping the user in place. Similarly, the EKTO ONE[1] uses wearable robotic boots that also allow the user to walk naturally in space. These boots have wheels at the bottom that are used for resetting the position of the users in the tracking area, as they walk. These techniques allow the users to walk beyond the limits of the physical area, which leads to increasing the feeling of immersion while minimizing the motion sickness since real motion is applied.

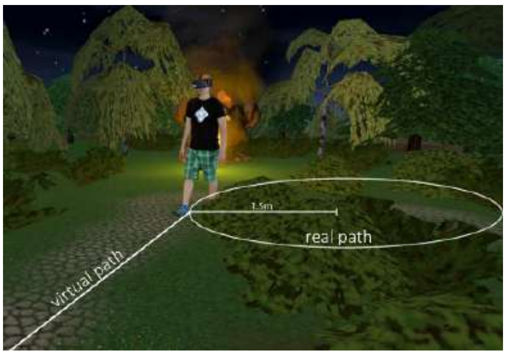


Figure 2.17: TeleWalking an RDW technique [53].

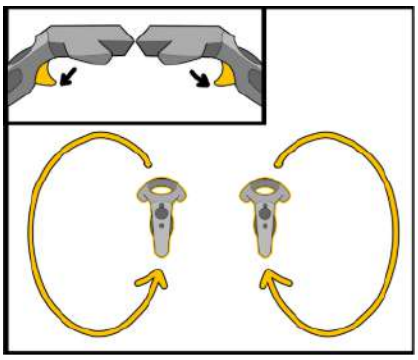


Figure 2.18: Arm Swinging gesture[19].

Figure 2.19: ODT KatWalk-VR.

[1]`https://ektovr.com/`

2.4.3 Artificial

Artificial LTs are the techniques in which the user doesn't provide any physical movement, but locomotion is enabled differently by utilizing input devices to direct VR motion and navigation, such as the controllers. By pressing a button, or moving the joystick or D-pads, enables the user to move in a certain direction in the VE. These methods follow the traditional video games movement mechanics, that by using a keyboard and a mouse enables the movement of an avatar. All artificial LTs are considered ALTs, since they enable locomotion at scale, thus allowing the users to navigate enormous VEs, regardless of the size of the tracking area. However, they are considered unnatural and to reduce presence [9]. Those techniques can be divided into continuous and non-continuous. Continuous are the LTs that the virtual motion is accomplished with a sense of continuity, providing an uninterrupted movement in the VE, and non-continuous, are those in which the user moves from one point to another instantly [9].

The most common non-continuous LT is Teleportation (TP). TP allows users to instantly be teleported to a location that is selected by the user. The most common representation of TP is an arched beam that starts from the controller and ends on the ground. This interface allows the users to select the point to teleport onto Figure 2.20. It is undeniably one of the most comfortable VR locomotion solutions around, since it is suitable for limited tracking area, reduces motion sickness since there is no visible translation motion, and helps the users navigate long distances in VEs. Therefore, it is being widely accepted as the state-of-the-art LT at the time of this writing. However, despite the good performance this method seems to provide [15] [39], it is considered to have a low sense of presence [11] since it lets users do something that doesn't exist in real life. As a result of this unnatural effect, it can reduce immersion too. Moreover, TP discontinuously translates the user's viewpoint and avoids the optical flow. However, the absence of optical flow cues impedes path [7], which can lead to spatial disorientation [4]. This forces users to physically rotate to adjust their orientation either before or after the teleportation, which most of the time is not desirable. In the [76] and [13] they augment TP technique by giving the option to users to select their rotation after the teleportation. It prevented physical rotation, but it increased the interaction time for TP. A last major drawback of TP, is the reduction of spatial awareness and cognitive load that it has, in comparison to other continuous LTs. This happens due to the non-continuous displacement of users, making it difficult to build an accurate cognitive map. In the [51], they tried to overcome that issue, by finding new locomotion techniques, that will inherit the good effects of the TP, and it will avoid the reduction of spatial awareness.

A frequently used continuous LT, that allows the user to navigate large VE, with great immersion, is with Vehicles. The user enters a vehicle or a platform and uses that as the controller, to move in the virtual world. For example, imagine sitting in a car simulation wearing HMD, and driving on virtual roads (Figure 2.21). It is a technique that is being used for training simulations like airplanes and cars, but also personal use. This method provides high immersion, and it is suitable for traveling large distances. However, it is not widely accessible due to the high cost. Also, according to the virtual experience, different vehicle systems may be required, thus this technique cannot be generalized. Despite that, virtual vehicles can be used without the need to depend on real hardware. They can exist only in VR, and they are controlled automatically to navigate the users, so they can focus on different tasks. Although this is a clever solution, it limits game design alternatives and is likely to induce motion sickness since the user remains passive while the virtual world moves.

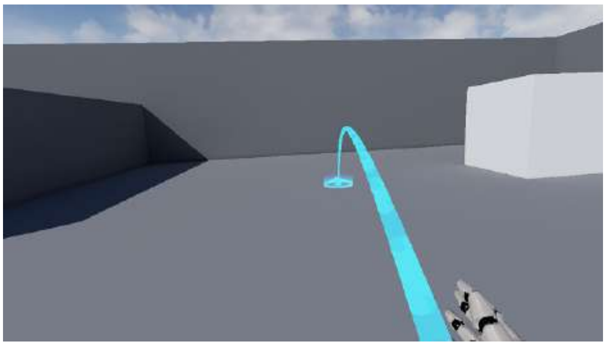


Figure 2.20: Example of teleportation representation in VR.

Figure 2.21: Car simulation.

Last but not least, one of the most used continuous LTs is Joystick- (JS) (or controller-) based. In literature, it is also referred to as Smooth Locomotion [35]. In this LT, users move through space as though they were in a first-person video game. The user is pressing directional buttons on the controller, and this continuously moves the user's viewpoint to the chosen direction. This control scheme resembles the default navigation technique in the non-VR games, and it is one of the most used [9]. It allows them to navigate beyond the limits of physical space, gives a better sense of continuity in the virtual worlds, and it does not exhaust the users, allowing them to travel long distances. However, this LT is strongly related to motion sickness. This is because users in VR get conflicting movement cues from proprioception and the vestibular sense compared to vision, as mentioned in the Motion Sickness subsection. Moreover, moving by the press of a button is unnatural, thus it is reported to break presence and provide low levels of immersion. In a lot of studies that compare this LT with others (that have been previously reported), like [39], [15], [8], [13], they highlight those issues. Nevertheless, this JS-based LT remains one of the most popular in the VR gaming community, since it is easily accessible, enables navigation at scale, does not require extra hardware, and gives a better sense of continuity. This Continuous Artificial Locomotion (CAL) technique based on Joystick is the technique that is being leveraged in our study.

To sum up, providing users with the ability to comfortably navigate in a VE, beyond the confines of the available physical space, while maintaining a high sense of presence, is something of paramount importance for user experience in VR. Therefore, locomotion is possibly one of the most researched aspects of interaction in VR. As a result, in the past decades, researchers have come up with numerous locomotion techniques, which they compare and improve constantly. In [9], they study many articles about virtual locomotion, and they detected 11 different LT. In the Figure 2.22 is shown the number of instances of the LTs that appear in the literature. According to it, the most popular LTs are the WIP, the JS and RW. In our research, we study the JS-based CAL to further explore the effects different sources of direction have in VR locomotion using this technique.

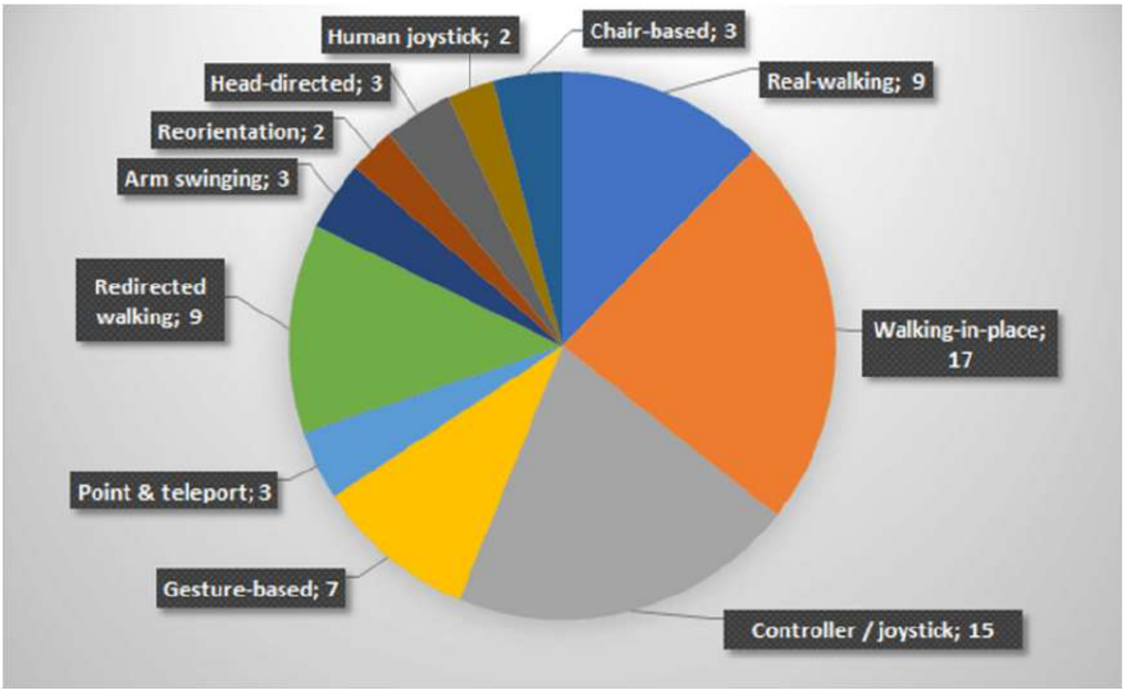


Figure 2.22: The 11 locomotion techniques and their number of instances, as documented from the 36 reviewed articles [9].

3. EXPERIMENT DESIGN

The goal of this thesis is to evaluate the effects of different direction sources in CAL. Those effects are examined in terms of performance, motion sickness, preference and presence. To achieve that, we designed and created an immersive and interactive VE in order to conduct a user study. That VE served as the experimental ”canvas” for the evaluation. In this VE the users can navigate freely by pressing directional buttons on the controllers. In this chapter, we describe the 4 direction sources that we selected to evaluate, the three main tasks that we asked the users to perform, along with the VE and the interaction mechanics.

3.1 Direction Sources

In VR applications that utilize CAL, the navigation is controlled using the controllers. However, what defines the direction of the movement? Meaning, what determines the forward of the user? In the non-VR First-Person Shooter (FPS) games that utilize continuous movement, the movement is enabled by the keyboard (WASD-scheme) and the mouse is used to define the direction that the user will move to. Similarly, in a VR application, we need an extra input to define this direction. For this experiment, we select 4 different direction sources.

3.1.1 HMD

Our first selection and one of the most common approaches is to be defined by the HDM. This means that the direction of movement is driven from the HDM orientation, which is available since the HDM is already tracked by the tracking mechanism of the VR system. Moreover, the HMD in a VE functions as our ”virtual” head, so when it is used as the direction source, we move towards where we are looking at. With a first look, this behavior may feel normal, since in real life we look where we are moving to. However, it binds the direction of movement with the gaze of the users. Consequently, with this approach you cannot move in a direction different from the one you are looking to, making it difficult to look at the surrounding environment, while moving in a straight line. As a result, this inflexibility may restrict the users to move freely in the VE.

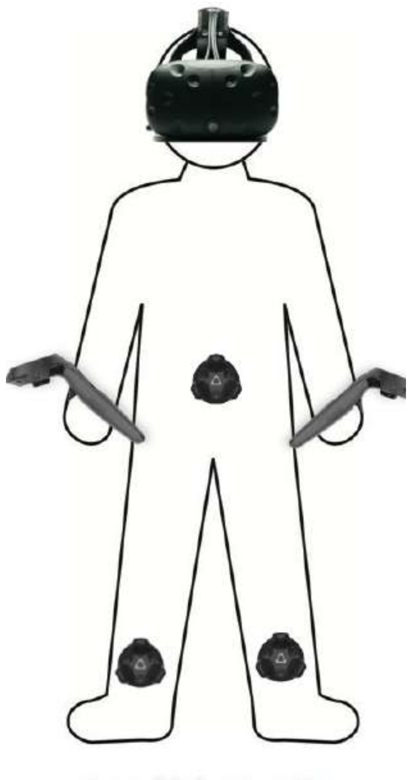


Figure 3.1: Equipment over the body of the user. The extra hardware consists of three Vive Trackers, one placed in the area of the Hip and two others over the feet.

3.1.2 Controllers

The second source of the moving direction that we selected is based on the Controllers. This means that the direction of movement is driven from one of the Controller's orientations. In our study, the direction is defined by the controller that is used to enable the movement. So, in this approach, the point of view of the users moves towards the direction that the used controller points to. This method is the second most common approach in the VR applications, since Controllers are also tracked by the tracking mechanisms and, just like the HMD, it does not require extra hardware. The controllers as a direction source allows the user to move independently of the direction that they look, and we believe that it can provide great flexibility to the movement, due to the low effort that is required for accomplishing large turns. On the other hand, this method may feel unnatural to the users that are not used to it. Furthermore, as it is already explained, the controllers in a VE are used as our ”virtual” hands. So, they are already used in order to interact with the VE. Thus, by overloading the hands with navigation functionalities, it may have an effect on the performance of the users.

3.1.3 Hip

In the third method, locomotion is directed using a body-centric technique [27], specifically based on the Hip. To achieve that, the hip is tracked by a tracker placed on the hip region of the user's body Figure 3.1. Thus, the direction of movement is driven from the orientation of this tracker. In this way, the user moves towards the direction that the hip is facing. That allows the users to move independently of where they look, and also it decouples the controllers from the locomotion direction control. These features may provide the users with more capabilities to navigate and interact in a VE. Besides that this method requires extra hardware to be implemented, it is already a well-known method in the VR community, and it can be easily replicated by using devices like smartphones[1]. As it is already mentioned, there are existing applications for smartphones, or other gadgets that are sold in the market like DecaMove[2], that are able to acquire the orientation and to forward it to the VR system. In this way, by placing the smartphone in that area, you can use it as a direction source easily. However, in this study we chose to use a Vive Tracker 3.0 due to the high accuracy and the stable operation that it provides.

3.1.4 Feet

For the last direction source, we designed and implemented a Feet-based technique. In this method, both of the user's feet are tracked by a tracker attached on each foot Figure 3.1. The direction of movement is calculated as the mean rotation in the YAW axis of both of the trackers. An example on how the direction rotation is calculated can be seen in the Figure 3.2.

Therefore, in order for the users to turn, they have to adjust their feet to look at the desired direction. This direction source is our proposed technique, and it was inspired by the promising results that were shown in the study of Willich et al. [63]. In their paper, they proposed a teleportation-based LT that is enabled by the feet only, utilizing trackers and pressure sensors for getting the necessary input. The results showed that the users enjoyed this technique more than the original teleportation. Using a similar rationale to ours,

[1] https://play.google.com/store/apps/details?id=org.ovrgyrotrackersync&hl=el&gl=US
[2] https://www.deca.net/decamove/

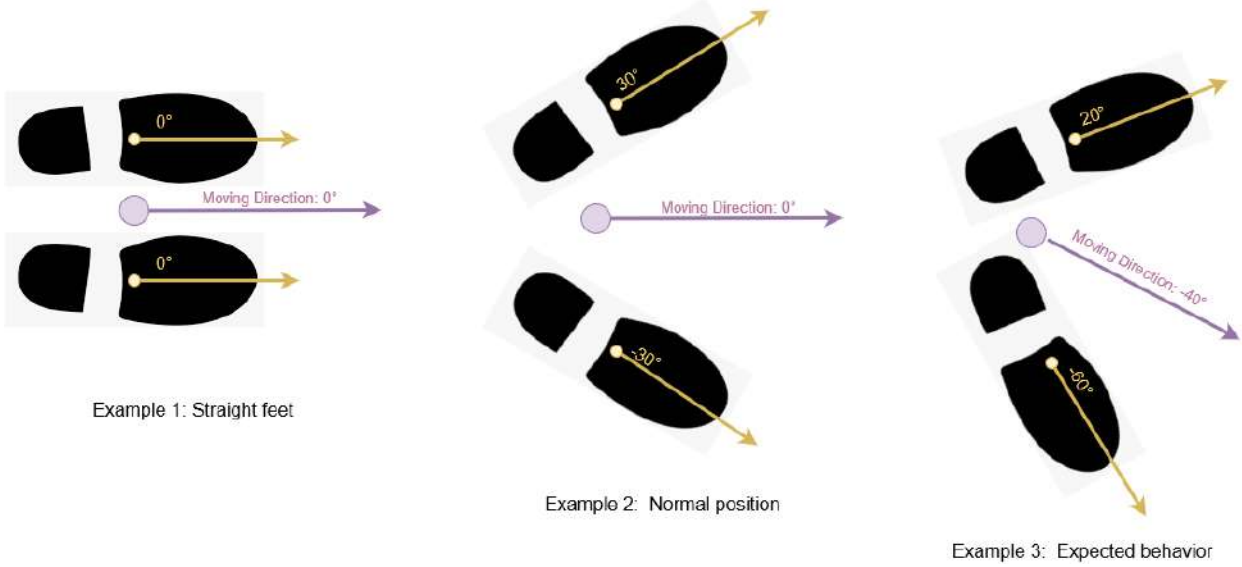


Figure 3.2: Feet-based direction method: 3 example of how the moving direction is calculated

they highlight that the hands are mostly used for interaction and the head for visual exploration. Thus, the feet could be used for locomotion, just like in real life. Therefore, similarly with the Hip-based method, this method decouples the head and hands from navigation functionalities, allowing the user to look and interact freely. Furthermore, since the users have to move their whole body in order to perform medium or large turns, we strongly believe that this movement will decrease the introduced motion sickness, because their body will exhibit more movement and the sensory conflict will be reduced [40]. Moreover, this method has greater hardware demands from the aforementioned methods, because it requires two trackers placed on feet, but there is no other more accessible solution currently available.

The aforementioned direction sources have been selected for the following reasons: headset-based and controller-based direction sources are the most commonly used approaches in VR applications. These devices are already tracked by the tracking system and also, they do not require extra hardware. Moreover, those techniques are the most common approaches when it comes to CAL. The Hip-based direction source is considered to be a realistic approach due to its resemblance to real life. Also, it is a well-known method in the VR community, but it has not been studied about its efficiency. The feet-based direction source essentially maps and utilizes the locomotion functionalities of human feet, which resembles the physical world. Moreover, the last two approaches offer the advantages of decoupling the headset and controllers from navigation functionality tasks; they are feasible with few extra trackers; and they leverage full-body tracking, which most probably will become the industry standard in the near future.

3.2 Hypotheses

Our hypotheses for the different direction sources in terms of performance, preference, motion sickness and presence are the following:

Performance is measured as a combination of multiple objective data that are collected from the VE as the users perform a task. These data are related to the duration that a task took and the accuracy of performing it. The users are asked to navigate complex spaces, with a lot of turns and twists, observe the environment while navigating, and interact with the environment by using the virtual hands while executing a simple task. In all of them, we calculate the total performance of the users for each method.

- **(H1) The Feet method will have the best performance with regard to accuracy.** About the accuracy in performing tasks, we assume that the feet method will stand out, since it does not overload the headset and the hands with navigation functionalities, thus the users would be able to be more efficient [30][8].
- **(H2) The Controllers method will have the best performance with regard to duration.** The Controllers method allows users to turn and rotate easily by providing the least physical movement between the other methods. It is the most flexible method since the users can turn around fast by only simply turning their hand to the proper degrees. For this reason, we believe with this method, the users will have the least duration.

Motion Sickness Motion sickness is measured by the symptoms that each method induced to the users after they completed all the requested tasks with it.

- **(H3) The Feet method will induce the least motion sickness.** In most of the studies, such as [13][48], they have found that JS-based methods like CAL induce the most motion sickness compared to other LTs. In all those studies they utilize either the Headset or the Controllers as the main direction source. In comparison, our proposed method, the Feet, requires more physical movement in order for the user to rotate. In this way, we believe the sensory mismatch will be less, leading to less induced motion sickness.

Preference is measured after the users have tested all the direction sources. This category includes how efficient, natural and fun each method was perceived by the users.

- **(H4) The Feet method will be considered as more natural.** Due to the fact that the feet are already involved in physical movement in the real world, the users may find it more natural than the others.
- **(H5) The Headset-based method will be considered as the easiest to use.** The Headset method is already the most used direction source [58], thus many users with experience in VR will find it as the easiest to use. Moreover, in VR, many times we assume that we are represented only by our head, so it may feel more reasonable to be directed by the head.
- **(H6) The Feet-based method will be considered as the funnest to use.** We assume that because feet are an extra body part that is involved in the virtual experience, making it funner, and also they already take part in locomotion in the physical world.

Presence is measured by how much each method made the users forget the real world and believe that they are located in this VE.

- **(H5) Both The Hip and Feet methods will create the strongest sense of presence.** Our hypothesis is that Hip and Feet-based direction sources will be preferred due to the direct relation with the way moving direction is defined in real life, and because they decouple the head and the hands from navigation functionalities.

3.3 User Virtual Representation

In most VR applications, the avatar of the user consists mainly of their hands only, since we cannot see our head. In some rare cases, the avatar is composed of an entire body that moves according to the hands and the used LT. In this study, we avoided providing a whole body to the avatar, even though we leverage full-body tracking. The reason was that we did not want to saturate our experimental goals and the focus of this study with other aspects of VR interaction, such as the virtual embodiment and the sense of ownership.

Therefore, the hands of the user are visualized using the SteamVR Hand Slim[3], which contains the animation for the fingers. The HMD has no visualization since the users cannot see their head. About the rest of the hardware that is being used, meaning the three trackers, our first approach was to use a 3D model of the Vive Tracker, so it would resemble reality. However, after some preliminary tests with users we decided to change that, since these visual objects reminded them of the real world. As a result, these cues from the real world may introduce breaks in the sense of presence of the users [75], and we wanted to avoid that. Therefore, we replaced the tracker's shaped objects with other, more relevant and suitable items, that were consistent with the rest of the avatar representation. For the tracker in the area of the hip we used a Buckle, and for the trackers in the feet we used a pair of boots. Those objects followed the movement of the trackers in real life, giving a sense to the users that they were wearing them. The representation of the user can be seen in the Figure 3.3.

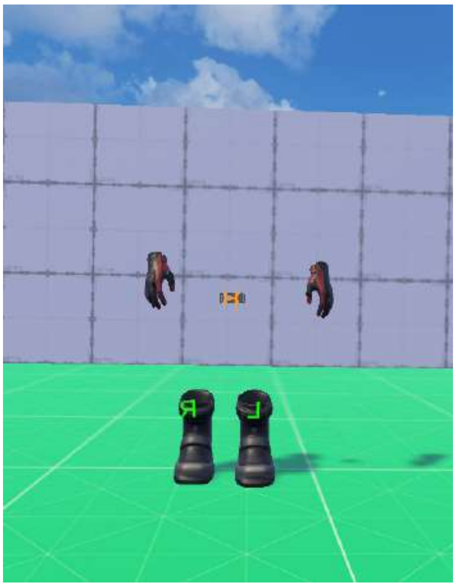


Figure 3.3: The representation of the user's avatar.

3.4 Virtual Environment

The VE was designed as simple as possible yet realistic looking for immersion purposes. Our goal was to create a VE that the users will enjoy, and it will make them feel comfortable and relaxed. Also, not too complex in order to avoid distracting their attention. We used simple materials mainly with gray, green, brown and white colors, in order to be minimal. The map was decorated with plants and palm trees, to create a feeling of an exotic place, and the sky was set to a blue sky with few clouds and a setting sun. We avoided adding a roof to the map, because we did not want to create any feeling of claustrophobia. As for the ambient sound, we used a light forest sound with some birds in the background. In the Figure 3.4 is shown a part of the map.

For the implementation of the experiment, three scenes were developed:

- **Training Scene**: in which the users were trained about the mechanics of the virtual application,
- **Experiment Scene**: in which the experiment was taken place,

[3] `https://i.ytimg.com/vi/4SjFplCCkdM/maxresdefault.jpg`

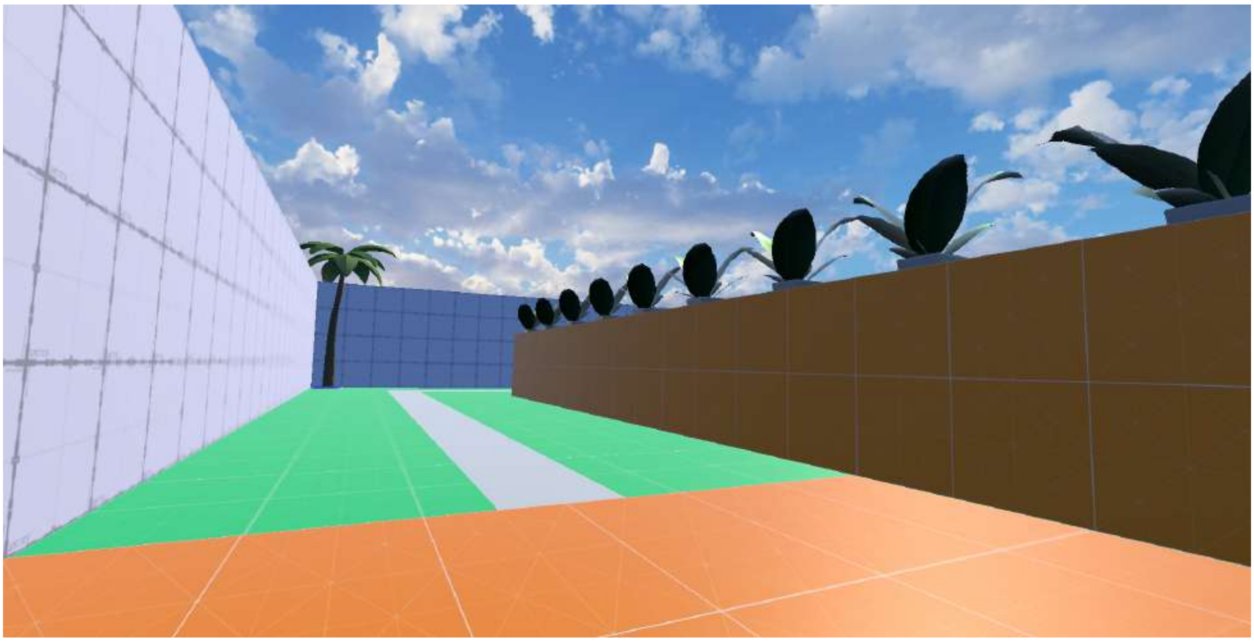


Figure 3.4: An example of the designed VE that was created for the experiment.

- **Final Scene**: which was for conclusion purposes, and it was used to inform the users that the experiment was completed, and to thank them for their participation virtually.

Furthermore, we wanted the environment to be well explained and self-guided, so we don't have to break the user experience for guidance. In this way, it was enriched with multiple tutorial speeches, explanation texts on screens and highlight arrows for guidance. All those items were used to guide the user in the environment.

3.5 Designed Assets

For the correct functionality of the VE, some assets were created and repeatedly used in the map. Those assets are mentioned below:

- **Gate**: A 3D gate that opens by the push of the blue button by the users. This button is highlighted by a yellow arrow that moves up and down, and it is located above the button, in order to be easily noticeable by the users. The gate is not always available for opening, so the button and the arrow may be missing. This is happening when the users should fulfill a pending task before they move on. When the gate opens, a sliding gate sound along with an animation is playing, and an action is triggered. This action is different according to each use-case. Therefore, this gate is mainly used to separate the tasks from the user and control the flow of the experiment. The appearance of this gate can be seen in Figure 3.5 (c).
- **Barrier**: A glass wall, which allows the users to see through it, and prevents them from moving forward. This wall is disabled when an action is completed. The moment this happens, a moving down animation along with a regular sound-effect is triggered. This barrier, most of the time, is used for tutorial purposes. The users should wait and listen to the whole tutorial speech before starting a task. An example of this barrier can be seen in Figure 3.5 (a).

- **Screens**: A black screen similar to a classic TV. It is used to show text to the users, like their performance. Also, it is used to show tutorial texts before they proceed to a task area. An example of this screen can be seen in Figure 3.5 (b).

- **Input Panels**: A black panel that is used to get input from the user in the VE. This panel can contain one or more questions for the users. For each question, the user should submit an answer. Most of the time, these answers are digits, and can be in the range of 0-9. In some questions, it is allowed to select two digits in order the users to input a two-digit number, like using a calculator. Also, there are some other available options in this panel, mainly for navigating through the questions. For selecting an answer, the user hovers over it and clicks it, with the trigger button. Then they can move to the next or the previous questions by pressing the ”Next” or ”Back” options. If they want to clear their answer, they can use the ”C” option, and if they have answered all the questions, they can submit them by pressing the ”OK” option. With each selection, a click sound is playing, and on the submit, a message is displayed to the users. Until the users submit their answers, they are blocked, and they cannot continue the experiment. When they do, an event is triggered that lets the users move to the next tasks. This event can make a button of a gate appear along with a highlight arrow, informing the users to use it in order to continue. An example of that panel can be seen in Figure 3.5 (d).

- **Colored Capsules**: A capsule that is being used for placing cubes. This capsule only accepts cubes with the same color. So, the users can grab a cube and according to its color, they have to place it in a capsule with the same color. This capsule can be seen in Figure 3.5 (f).

- **Item Source**: This asset spawn the cubes. Those cubes can be grabbed by the user, and they should be placed in the aforementioned capsule with the same color. When this asset is filled with a cube, it is highlighted with an arrow above that moves up and down, in order to be easily noticeable. An example of this asset can be seen Figure 3.5 (g).

- **Walk-in Areas**: A highlighted area that the user should walk inside. It is used to show the users where they should go. When they get in, it disappears, playing a “success” audio effect and triggering an action. An example of it can be seen in Figure 3.5 (e).

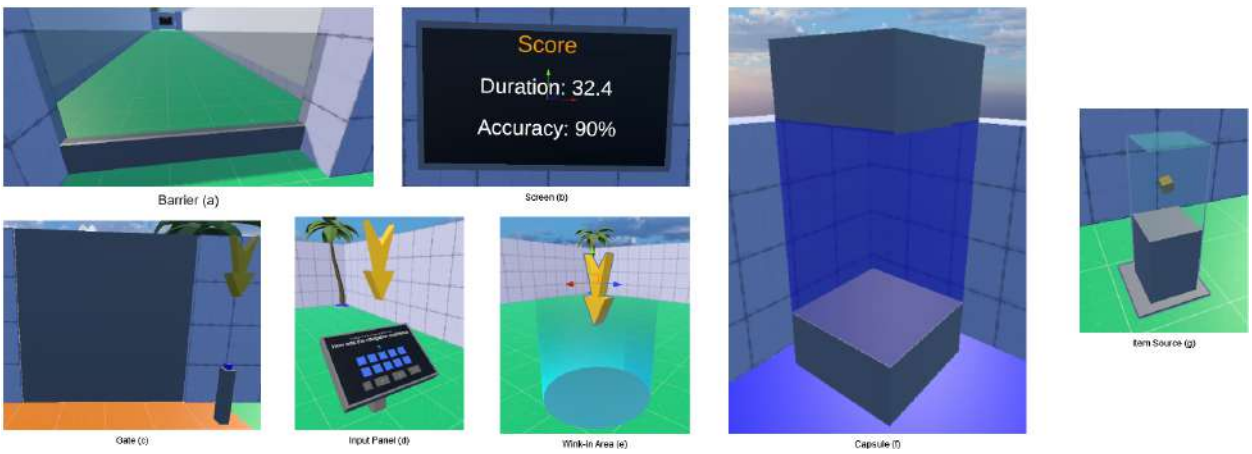


Figure 3.5: The created Assets.

Table 3.1: The utilized Latin Square Matrix

CONTROLLERS	HEADSET	HIP	FEET
HEADSET	FEET	CONTROLLERS	HIP
HIP	CONTROLLERS	FEET	HEADSET
FEET	HIP	HEADSET	CONTROLLERS

3.6 Experiment Tasks and Parts

This section describes the three tasks that we designed in order to evaluate the selected direction sources. Each task takes place in a different part of the VE. As it is already mentioned, three scenes have been created. The evaluation of the sources takes place in the second scene (**Experiment Scene**), which contains the main tasks, and it is repeated with all the four direction sources. To avoid ordering effects, we used the Latin Square method [69] which utilizes a 4 x 4 matrix, having in each row and in each column all the four methods in different positions. This matrix defines the order that the methods will appear to the users. Without this way some methods would benefit by the order since as the experiment passes, the users are getting used to the VE, the tasks and even to the navigation functionality. Moreover, the induced sickness and fatigue is aggregated as the experiment passes, so it would be unfair for the methods that will appear in the end.

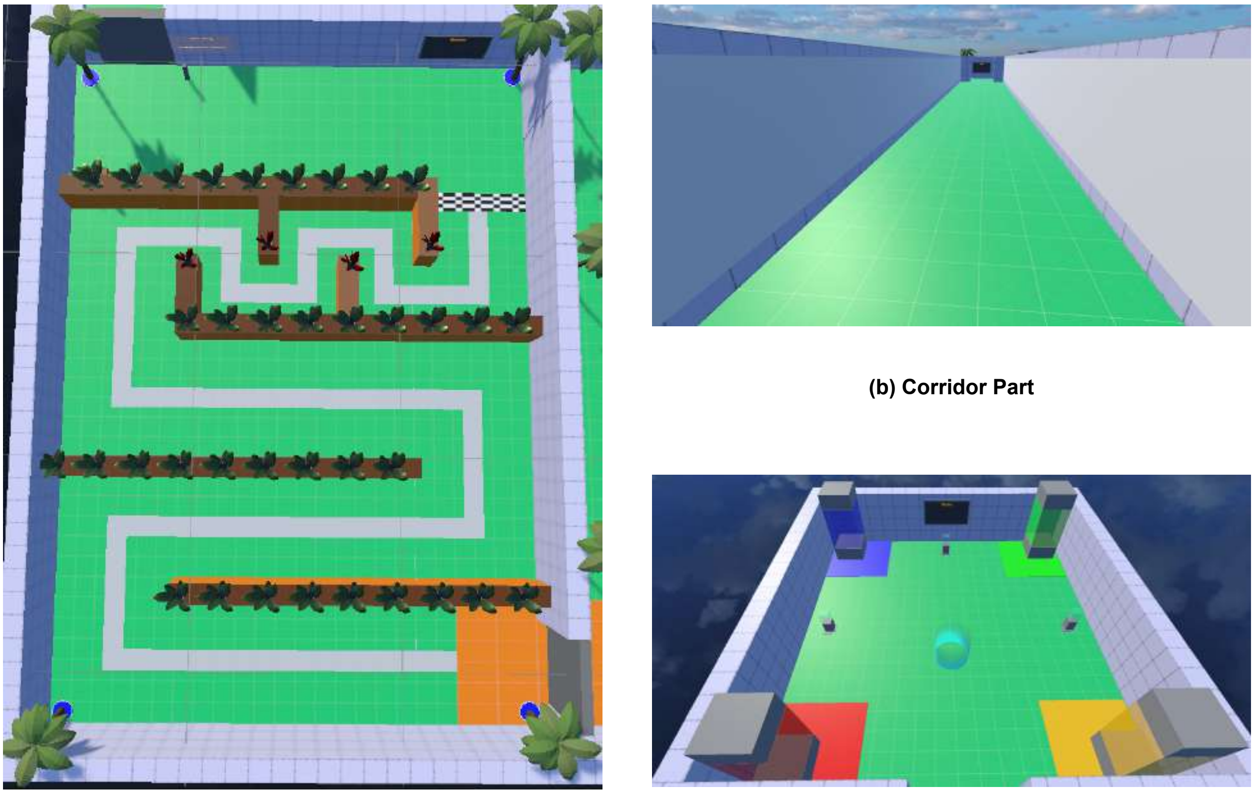
The Latin square matrix can be seen at Table 3.1.

The parts of the VE are described with the same order as they appear to the users during the experiment.

3.6.1 Tutorial

The first part that the users are introduced to when the application starts is the Tutorial. This part aims to teach the user with the basic mechanics of the VE, so they are prepared for the experiment. Those mechanics include how to navigate in the VE, how to grab cubes, how to place cubes in capsules and how to interact with the input panels. As for the utilized direction source, we chose to select the HMD, so the users move towards where they are looking at. Besides that this selection may not be fair against the other methods, we had to select one of them, and the head-based is used as the default method in most VR applications with CAL.

This part takes place in the training scene, which is the first scene that loads the application. When it starts, a tutorial speech starts to play. It firstly welcomes the users to the experiment, and then it explains to them how to move around using the controllers. Moreover, the users can see some visual hints on the controllers in order to better understand how it works. The said speech is also written in a Screen, that is located next to the spawn area of the user, in order to be able to read it. Until the speech is done, the users are limited in an area where they can test the navigation tips. This area is limited by a barrier Figure 3.7 (a). When the speech is over, the barrier is disabled and the user is asked to move to a walk-in area through a corridor. In the bottom of this corridor there is a white path, in this case it does not have any functionality, but works as an optical



(a) Zig-Zag Part

(b) Corridor Part

(c) Color-Game Part

Figure 3.6: Tasks in Virtual Environment

reference of the path they have to follow, just like they will find later in the first task of the experiment Figure 3.7 (b). When the users enter the corridor, a sound is playing to inform them that they have successfully entered the area that leads to the correct path. When the users reach their target, marked by the walk-in area, their performance time appears on the screen and a speech informs them of their performance. In that way, they understand that the time started to count along with the previous played sound. As the speech is over, a barrier of the right of the user gets disabled, unlocking the next room. In the next room, the user first learns how to grab a cube, how to place it in a capsule, and then how to open a gate by pressing the button. All those actions are explained by a speech, by texts on screens and by visual hints that appear on the controllers of the user. The appearance of this room can be seen in the Figure 3.7 (c). By the opening of the gate, the last room of the training is revealed. In this area, the users learn to use the input panel. Just like before, the user learns how to do it by the tutorial speech which is also written on a screen and again by visual hints. This last room is shown in the Figure 3.7 (d). The users are asked to answer a dummy question which has as available answers ”Yes” or ”No”. Regardless of their answers, the training is complete, the speech congratulates them, and it informs them that they will continue to the next scene in which the experiment will take place.

3.6.2 Familiarization

In this part, the user gets to meet and practice the current direction source each time before moving to the first experimental task. It is the first part of the experiment scene, and it has no evaluation effect. When it loads, the users are placed in a limited area surrounded by barriers. This limitation was introduced, in order to prevent the users to

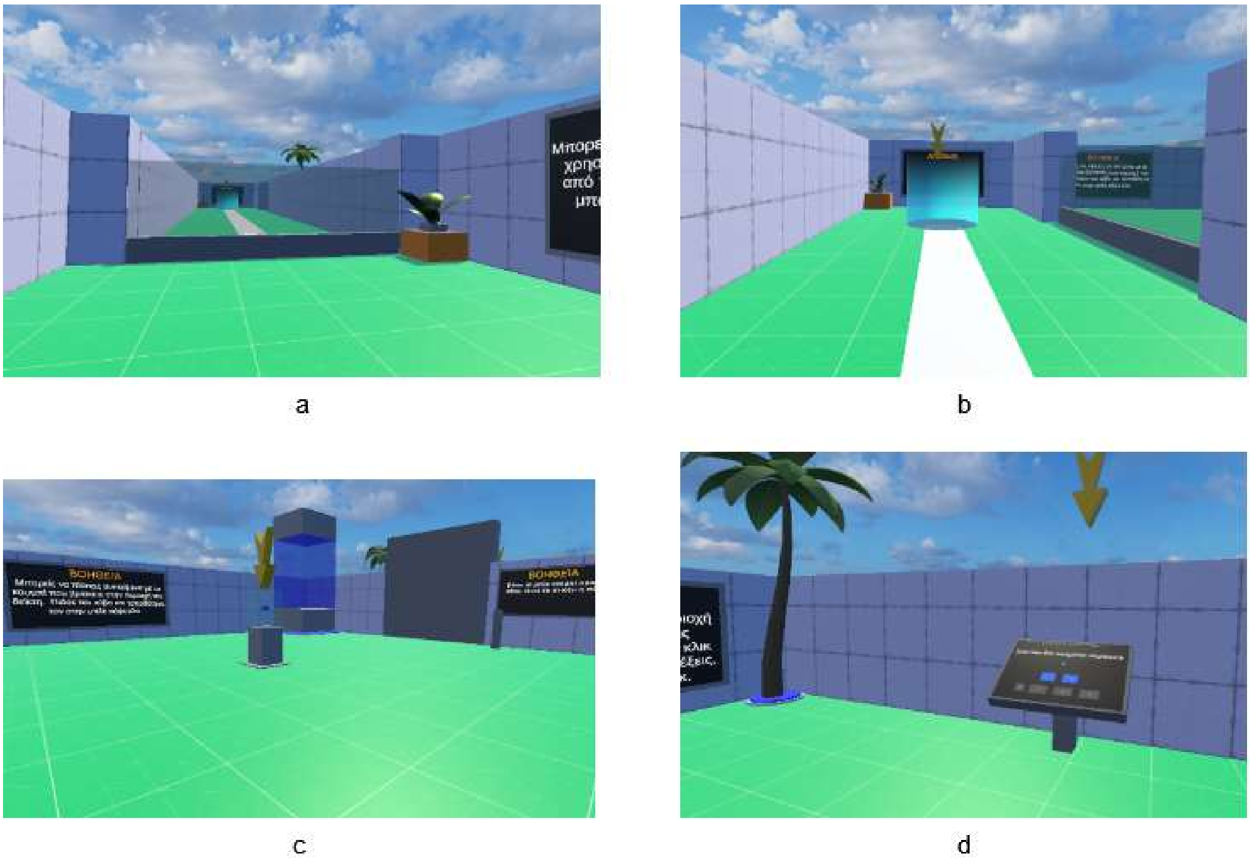
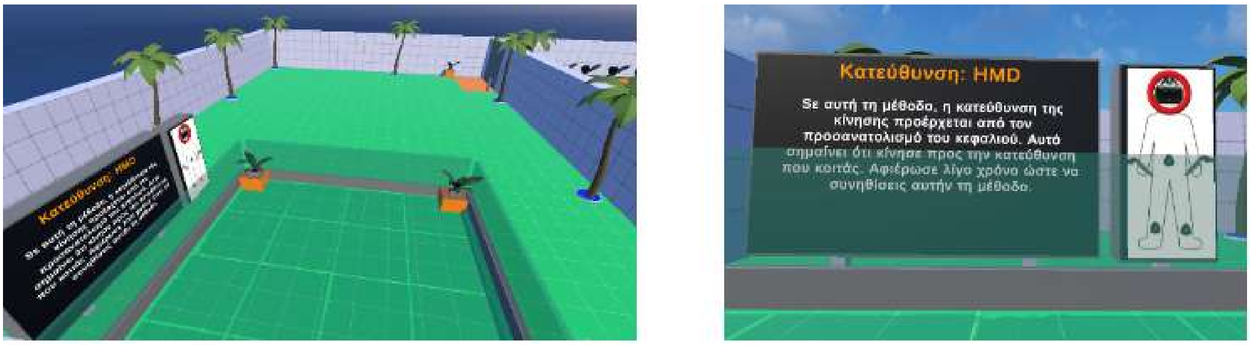


Figure 3.7: The rooms of the Training Part.

move around before they get informed about the current direction source. Next to the barriers, there is a large screen that informs them about the current active method, along with a detailed description of it in text. Also, there is another screen next to it, which contains a representation of the user with the equipment, that visually shows the users which of the equipment directs the hardware. Those screens can be seen at: Figure 3.8 (b). When the experiment starts, a voice introduces to the users the current direction source that it is currently active, explaining to them how it works, by telling them what is already written in the detailed description of the first screen. When the voice is finished, the barriers are disabled and the users are asked to do a bit of training in order to get more familiar with this method. Then, a walk-in area appears, and the users have to go there. When they do, another one appears in a different position. This task is repeated one more time. Then, the training part is complete, and the voice informs the users that they can start the experiment by moving through the enabled gate, but also encourages them to practice as much as they want, and to continue when they feel ready. The users can practice there freely with the current method. When they feel ready they can move on by opening the gate, as they have been taught, that leads to the next part. The appearance of that part can be seen in the Figure 3.8 (a). The training part was designed to force the user to train and get familiar with each method before they move on.

3.6.3 ZigZag Task

As the users pass the gate of the Familiarization Part, they enter the ZigZag Part. This part is the first task of the experiment. Through this task, we aim to evaluate each direction method in a challenging navigation path with multiple turns. It contains 13 turns of 90°, in



a b

Figure 3.8: Familiarization Part.

which the 7 of them are very close. On the floor there is a white path which the users are asked to follow and stay inside it as much as they can. The trajectory of the path can be seen in Figure 3.6a In this way, we measure the accuracy of each method. The first time that the user enters this part, the path is blocked by a barrier. The user gets informed by a tutorial voiceover about the objective of this part. Also, there is a screen next to him/her, that contains all the said explanations about the part. When the tutorial speech is over, the barrier gets disabled. This happens only the first time the user enters this part, regardless of the source. The entrance of this part can be seen at Figure 3.4, but without the barriers.

As the users enter the task area, by passing the neutral area which is with orange color., a sound signals the start of the performance evaluation. The part is completed when the users complete the path, meaning when they pass the finish line at the end of it.

The performance time and the accuracy are printed on a screen placed at the end of the task, so the users get informed about their statistics. Due to the multiple turns and CAL nature, the users may feel some motion sickness as they end this part. For that reason, there is a neutral area before the user moves to the next part. So the users can relax in this place for a bit. In this area, first we had placed an input pane in order to get some feedback on that point from the user about the current method, but then we decided to remove it.

The appearance of this part can be seen at Figure 3.9.

3.6.4 Corridor Task

On the end of the neutral part of the last part, there is a gate which leads to the next part. On the right side of that gate exists a screen that informs the users about the next task. For the next task, the users have to walk through a straight corridor. In both sides of that corridor, there is a wall, in which some dots appear. Each dot appears only when the user is closer than a specific distance to it. So, the users are asked to count those dots as they walk through that corridor. In the end of the part, there is an input panel, in which the users submit the total amount of the dots that they count.

Just like the previous part, when the user enters that part for the first time, there is a barrier that prevents the user from starting the part until a tutorial narration plays. As the narration plays, both of the walls are highlighted with an animation in order for the users to better understand what they have to do. After that, when the user enters the corridor, a sound plays, signaling the start of the clock. As the users cross the corridor, they have to look left

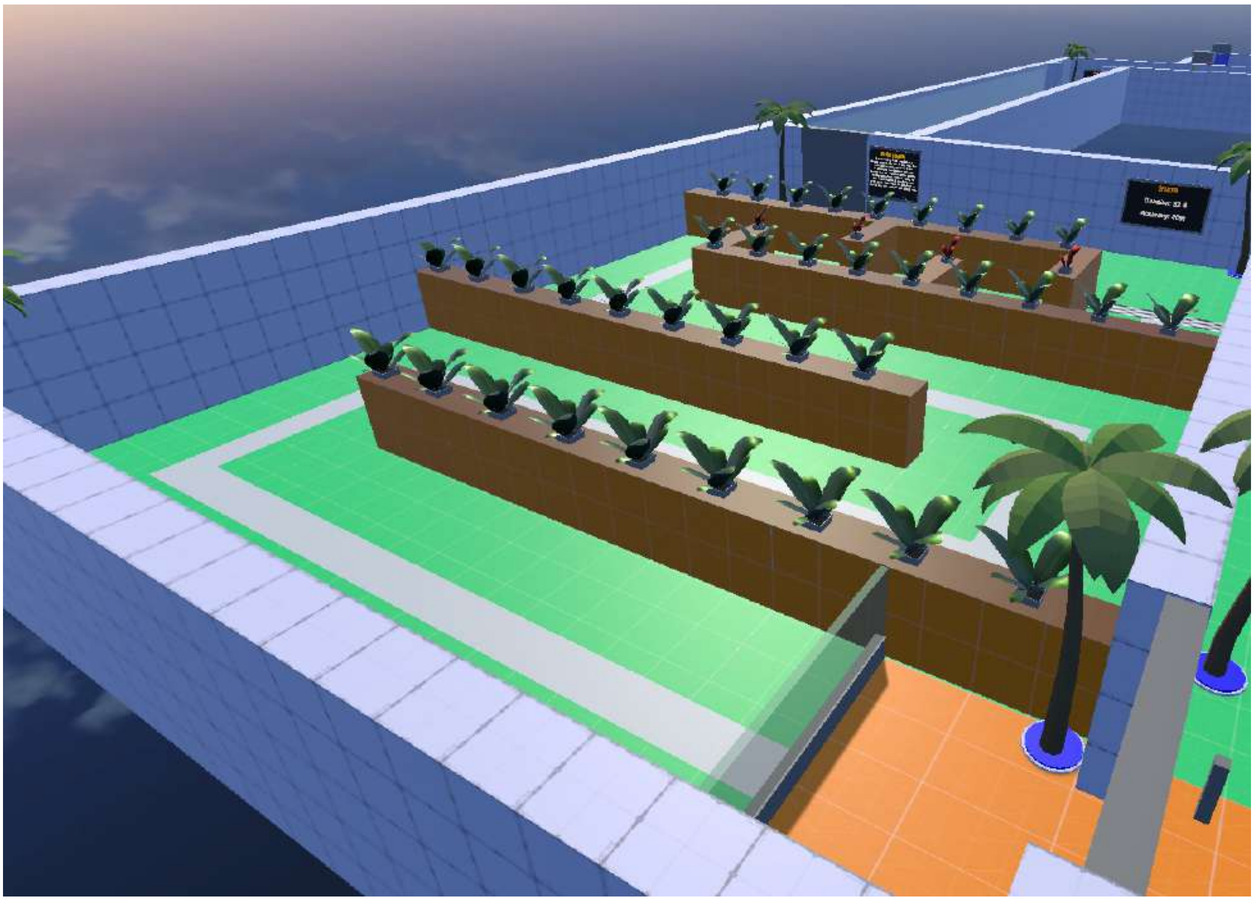
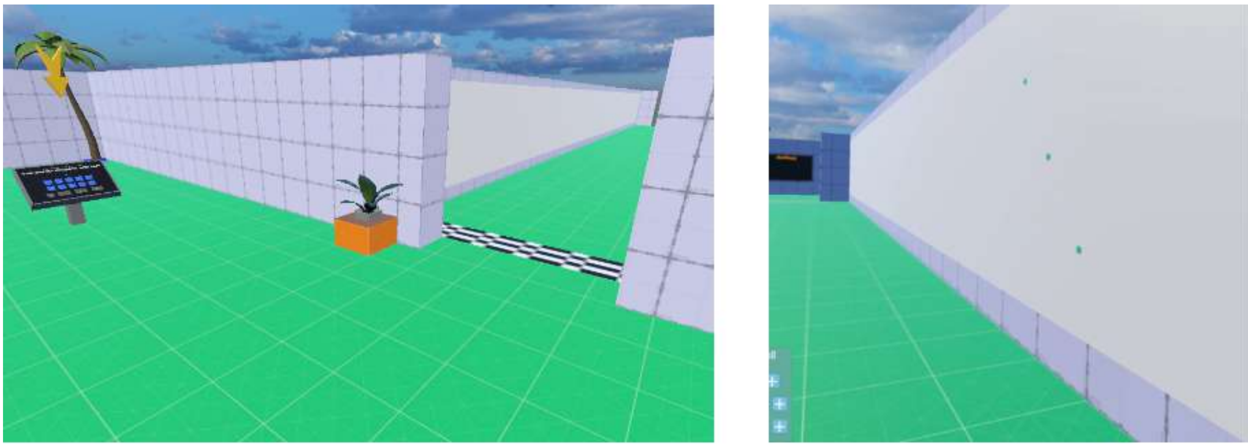


Figure 3.9: ZigZag Part.

Table 3.2: The number of dots that appears in each method.

	Left Wall	Right Wall	Total
HMD	7	6	13
Controllers	7	7	14
Hip	5	11	16
Feet	9	6	15

and right in order to count the dots that appear. At the end of the corridor there is a finish line. When the users cross it, another sound plays that signals the stop of the counting. Also, at that moment, a screen appears in front of the user that shows his/her duration in that part. After the user finishes, all the dots disappear, and the user cannot get back to count them again. In the room after the finish line, there is only an input panel, in which they submit the number of the dots that they counted. The starting part of the corridor can be seen at Figure 3.10 and the ending part with the finish line and the input panel at Figure 3.10.



Ending of the Corridor   Dots Example

Figure 3.10: The ending part of the Corridor.

This part was designed in order to evaluate the spatial awareness and the effect on the visual observation that each different direction source causes. Also, it is very common to look around while we navigate, so we believe that represents a real case scenario of VR applications. It is inspired by the [51], in which they study how different LT affect the spatial awareness of the users.

The amount of dots placed on each wall is different for each method. In this way, the users will not automatically assume the right amount after the first pass. The number of dots that we decided to place are seen in the Table 3.2. Also, the dots are appearing in a random position on the wall, each having a different padding from the bounds of the wall. So in different users, in the same method, the amount of the dots are the same, but not in the same position.

After submitting the number of counted dots, the button of the gate in front gets enabled. The user is then ready to move to the last part.

3.6.5 Color Game Task

For the last part, the users have to complete a mini interactive game. In this game, there are four colored capsules (Blue, Green, Red and Yellow), each one placed on each corner of the room, and three item sources on the sides of this room. These sources are referenced as North, West, and East according to their territorial position. The appearance of this part can be seen in Figure 3.6c and also in the Figure 3.11. In this part, the users have to grab the cube from the highlighted item source, and place it on the capsule with the same color. Then, another cube appeared in one of the sources. This action is repeated four times, once for each color, in order for the game to be complete. When the game is complete, the user's performance time appears on a screen that is located in front of the North *item source* position. Also, an input panel appears in order to ask the user about the method they used throughout this method-session.

We designed this task, in order to evaluate each method on a highly interactive game, that requires hands-busy for interactions and complex navigation with many turns. It requires the users to use their hands to interact with the environment constantly, and it includes many turns and backs and forwards, so it forces the users to follow complex navigation patterns. As a result, it is an ideal task to check our direction sources. Furthermore, it requires the user to look around in order to identify the correct capsule and the highlighted source.

Just like all the other parts, when the gate for this part opens, the path is blocked by a barrier only for the first time. The tutorial voice plays and describes in detail what the user should do. All the said information is also written on a screen on the right of the user. When the tutorial voice stops, the barrier gets disabled. In order to start the experiment, the users should go to a walk-in area in the center of the room. When they enter it, a sound signals the start of the tasks. The room, as the users see it, is shown in Figure 3.12.

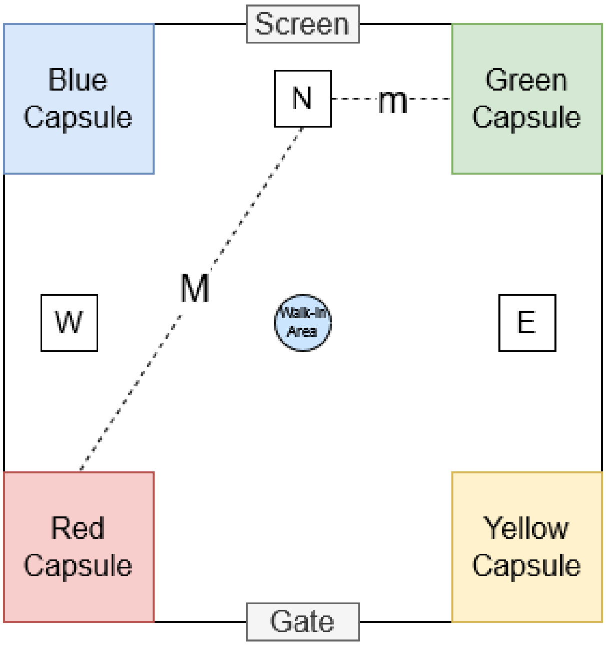


Figure 3.11: The territorial structure of the Color Game Part.

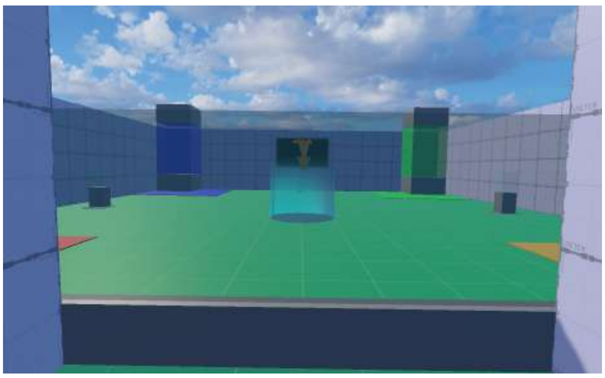


Figure 3.12: The Color Game Part as the user sees it for the first time.

The location and the color of the cubes appeared were different for each direction source. However, in order to be fair among the methods, we used a distance and a rotation protocol. About the distance protocol, we categorized the distances in large distances (M) and small distances (m). An example of these distances can be seen in Figure 3.11. Therefore, all the methods had to sum in the same total distance. In the Figure 3.13 can be seen the patterns and the distances that were used for each direction source.

	Round 1	Round 2	Round 3	Round 4
HMD	N-R (mM)	E-G (Mm)	N-Y(mM)	W-B(Mm)
Controllers	N-Y (mM)	W-B (Mm)	N-R (mM)	W-B (Mm)
Hip	W-Y(mM)	N-G (Mm)	E-R (mM)	N-B (Mm)
Feet	E-R (mM)	N-B (Mm)	W-Y (mM)	N-G (Mm)

m: SmallDistance
M: Large Distance

N: North
W: West
E: East

B: Blue
G: Green
R: Red
Y: Yellow

Figure 3.13: The action pattern that was used for the Color Game. Each cell contains: Spawn Location - Color of the Cube (Distance To Direction | Distance to Capsule).

Furthermore, the total number of rotations that were executed are also the same for each method. In this task, there are two categories of rotations that are mainly required to be performed by the users. When users grab a cube, then they have to perform a rotation to the desired receiver. Similarly, when they put the cube to the receiver, they have to rotate to the next item source. These rotations have to be at least either about 90° or about 45°. They can be seen in Figure 3.14.

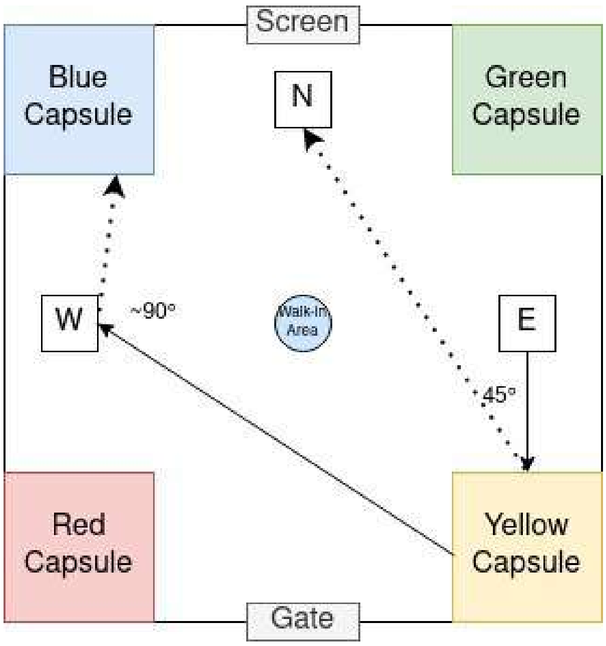


Figure 3.14: The two groups of rotation in Color Game.

Therefore, all the methods have the same minimum total of degrees that the users have to rotate. In more detail, this total includes at least four rotations of 45° and three of 90°.

After finishing the colorGame an input panel appears in this part that contains some questions about the used method. When the users submit the questions in the input panel, the evaluation of the current direction source is complete. The user is re-positioned in the Familiarization Part and all the map gets reset, as it was in the first place. Then the next method gets activated.

3.7 Mechanics

3.7.1 Movement and Interactions

The movement in this experiment is enabled by the controller, just like in the most CAL implementations. Specifically, by the analog stick, which is provided with directional information. Also, we decided to let the users be able to use whichever controller, left or right, they feel better with. Both of them were enabled for usage. The users could move to all directions with the relative direction stick. So, they could move forward, backward, left and right. At first, we had enabled only the forward vector of movement, in order the users to be forced to turn only using the current direction source. However, this behavior was quite weird and unexpected, so we decided to use the default scheme of movement, which is the one that the most VR applications with CAL utilize.

Next, the speed of the movement was not constant. It was set to be linear to the force of the user push in the directional pads of the controller. The max speed after tuning different values, set to be 4.5km/h. A speed that is not too fast nor too slow.

For interacting with the environment, we decided to keep a simple approach of using only one button in order to be simple for the users. So, we set all the interactions (grabbing and interacting with the input panels) to work with the trigger button.

The aforementioned buttons of the VE can be seen in Figure 3.15.

Figure 3.15: Controls in the Valve Knuckles Controller

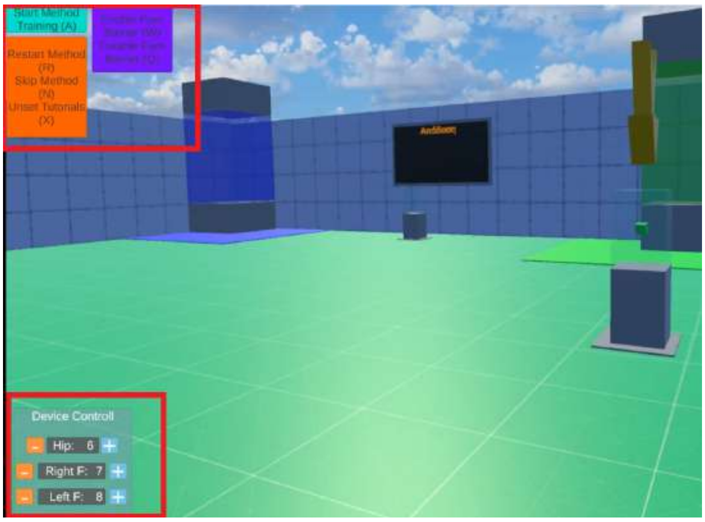


Figure 3.16: The controls that are enabled for the observer user.

3.7.2 External Control

For the better control of the user experience, some other mechanisms were designed and added. Those mechanisms can be activated by an external observer out of the VR, who has access to the high-end computer that supports the VE. Those aim to control the experience and to manage unexpected behaviors (crisis management) like the sudden shut down of the HMD and others. These mechanisms are visible only to the user in the screen of the computer and not in the VR. The observer can enable them by pressing them regularly as buttons with the mouse, or using bind shortcuts of the controller. Those buttons can be seen in the Figure 3.16, and they are located on the left side of the view.

At the top the left side we have the below controllers:

- **Start Training (A)**: This button starts the training of the current method to the user in the Familiarization Part. It was designed in order for the observer user to control when the next new method starts, since there are breaks to the user's experience between each method.
- **Restart Method (R)**: This button restarts the current method that the user uses. That was made in order to handle unexpected situations. Essentially, it repositions the user at the starting position in the familiarization part, and resets the map.
- **Skip Method (N)**: This control is used to skip the current method and to move to the next one. It was used in case that the user crashed, and we had to load the application again. Therefore, the user was skipping the tested methods.
- **Unset Tutorials (X)**: Similarly with the last control, if the application crashes, we restart it. So with this button we disabled the tutorials, so the user had not to listen to them again.

In the bottom of the view, there is a box that is used to calibrate the trackers over the user virtual body, in order to fit in the correct order. Essentially, it sets the correct ID in the relative tracker.

4. IMPLEMENTATION

Our goal for the implementation of this experiment was to create a stable and smooth virtual experience. Additionally, we wanted to make the users feel comfortable moving their bodies around, since the experiment requires a lot of turns and mobility. Therefore, the utilized equipment should not distract the users, so they can concentrate on the experiment's task. For these reasons, in this section, the implementation decisions we made are described, along with the reasons that led us to select them. We focus on the hardware that was utilized and the software that was used for the development of the VE.

4.1 Hardware

For conducting a VR experiment, we need a VR system capable of supporting the experiment's requirements and a high-end PC. Moreover, for our experiment we need three trackers, one placed on the hip of the users, and the other two placed on each leg. Those trackers should be able to acquire at least orientation of those body parts. Moreover, for controlling the movement, we chose a controller with a joystick since it is the most common way of navigating VEs with CAL, and many users are already familiar with it due to the strong similarity it has with the controllers of gaming consoles.

4.1.1 Trackers

In regards with the utilized trackers, firstly we checked the DecaMove and the OwoTrack applications that we mentioned in the previous section, in order to acquire the orientation of the additional body parts utilizing smartphones. These applications can calculate the orientation of the smartphone by gathering data from multiple sensors (like gyroscope, accelerometer and magnetometer) and then forward it to the VR system using networking. In this way, by placing a smartphone to the desired parts of the body, we can track the orientation of these parts. However, these applications were not operating in a stable manner and were not as accurate as we needed to. Consequently, this problematic functionality would break the experience of the user and hinder the results. Furthermore, it would be quite uncomfortable to place a smartphone on the legs of the users. Consequently, we had to turn down this option.

Therefore, we chose to use the Vive Trackers. As it is already mentioned, this device is used to track movement and to bring objects from the real world into the VE. These devices are being tracked by the inside-out tracking mechanism of the HTC Vive headset and in combination with their internal sensors, they provide pinpoint accuracy. As a result, this setup requires the lighthouses of the HTC Vive in order to function. More specifically, we used the **Vive Trackers 3.0**[1] which is smaller, lighter, and longer-lasting than the original ones. Furthermore, these trackers can be easily worn with specific straps for the legs and the hip. Last but not least, they are compatible with the SteamVR SDK which, as we are going to explain, is the utilized SDK for the experiment's implementation.

The main specifications of the **Vive Tracker 3.0** are shown below.

- **Weight**: 75g

[1] `https://www.vive.com/us/accessory/tracker3/`

- **Dimensions**: 70.9 × 79.0 × 44.1 mm
- **Battery Life**: 7.5 hours
- **Field of view**: 240°

4.1.2 VR Headset

As far as the utilized VR headset, since we wanted to provide the users a comfortable experience, and since the experiment requires a lot of mobility and many physical rotations, we decided to utilize a tetherless VR system. That was selected to avoid keeping the users focused, avoiding the cable as they move, since this can lead to breaks in presence. In this way, there will be no cable to distract them, so they can freely move, turn around and concentrate on the experiment's tasks. Therefore, our first selection was to use the **Oculus Quest 2**. This device not only offers a tetherless VR experience but also, it contains suitable controllers with joysticks for controlling the movement. Moreover, it is a stand-alone solution which would simplify the experiment.

However, despite the advantages of this selection, there was a big issue that we had to overcome. The **Vive Trackers**, are tracked from the tracked mechanism of the HTC Vive Headset, which leverage lighthouses. Consequently, the Oculus Quest 2 and the Vive Trackers were not in the same tracking space. So we had to find out how to have both devices in the same tracking space. Luckily, we were able to manage that issue using an open source software called **OpenVR-SpaceCalibrator**[2]. This software is used to track VR devices from one company with any other. More specifically, you set the tracking space of one VR system as the reference tracking space, and then, after some calibrations, you can see devices from other companies (like the Vive Trackers) into the same tracking space. Despite the fact that this approach solved our main issue, we had to do multiple calibrations since we use more than one tracker, and there were times that it did not operate stably, so we had to repeat the calibration process. So we could not use this approach in our experiment, since it overcomplicated the experiment. Therefore, we had to abandon the whole approach with the Oculus Quest 2 and find a new one.

In order to maintain a stable functionality with the trackers, we chose to use the **HTC Vive Pro** headset. In this way, all the devices appear in the same tracking space without any issues. However, this device not only works with a tether connected to the computer, but also the controllers have a touchpad for controlling the movement, which we believe was not ideal for our use case. In order to make this VR headset work tetherlessly, we utilized the **Vive Wireless Adapter**[3]. This device offers a tetherless, near-zero latency VR experience that's fast, responsive and with maximum performance. It consists of a Wireless Adapter that is placed over the headset, an antenna which is connected to the computer though a PCI[67] slot, and a battery capable to last for up to 2.5 hours, which we placed it over the strap with the tracker on the hip of the user. About the controller issue, we chose to replace the classic controllers of the HTC Vive Pro with the **Valve Index Controllers**. These controllers contain a similar joystick for controlling the movement like the one in Oculus Quest 2. In addition, they are more stable over the user's hand due to the straps on the grip. Furthermore, they provide finger tracking using pressure sensors that are located on the grip, and it is compatible with the SteamVR SDK (which we used). Last but not least, these controllers have battery life for up to 7 hours.

[2] `https://github.com/pushrax/OpenVR-SpaceCalibrator`
[3] `https://www.vive.com/us/accessory/wireless-adapter/`

Therefore, since we used the Vive Pro Headset, for running the VE we used a high-end computer. The specification of that computer are shown below:

- Operating System: Windows 10
- **CPU**: Intel Core i7-7700K Processor
- **GPU**: Nvidia GeForce GTX 1070
- **RAM**: 32GB

In the 4.1 are shown the utilized devices of our experiment.

Vive Trackers 3.0 | Vavle Index Controllers | HTC Vive Pro with Wireless Adapter (and Battery)

Figure 4.1: The used equipment for the experiment.

4.2 Software

For the development of the experiment, the Unity 3D Game Engine was used. The VE functionalities were implemented with C# scripts, which is the supported scripting language for this game engine. They were also accompanied by some downloaded assets from the Unity Asset Store[4]. For the scripting development, the Visual Studio[5] editor was used. All these software oriented implementations are described in detail in this section.

4.2.1 Unity

Unity is a cross-platform game engine developed by Unity Technologies, first announced and released in June 2005. Specifically, it is a developer tool that can be installed in all major operating systems (Microsoft Windows, macOS, Linux) and it is used for building from 2D and 3D to even virtual and augmented reality games. It is the magic behind many popular games, XR applications, interactive simulations and animations beyond the gaming industry. Moreover, this engine allows users to create experiences for more than 25 platforms, including mobile, desktop, consoles, and VR headsets. Besides the video game industry, Unity has been adopted by other industries as well, such as film, automotive, architecture, engineering and construction [73]. Despite the fact that the engine is written in C++, it allows developers to write their code in C#.

[4] https://assetstore.unity.com/
[5] https://visualstudio.microsoft.com/

Unity provides a user-friendly graphical editor allowing users to draw shapes, work with cameras, apply materials without writing a single line of code. This editor is suitable for creating 3D environments, levels, menus, animations, writing scripts, and organizing projects (Figure 4.2). The users can assemble assets into scenes, add lighting, audio, special effects, physics and animations, through an iterative process of editing, testing and playing that are happening seamlessly inside Unity's editor. The tool's intuitive structure and quick, productive workflow helps users produce interactive content, lowering the required time, effort and cost.

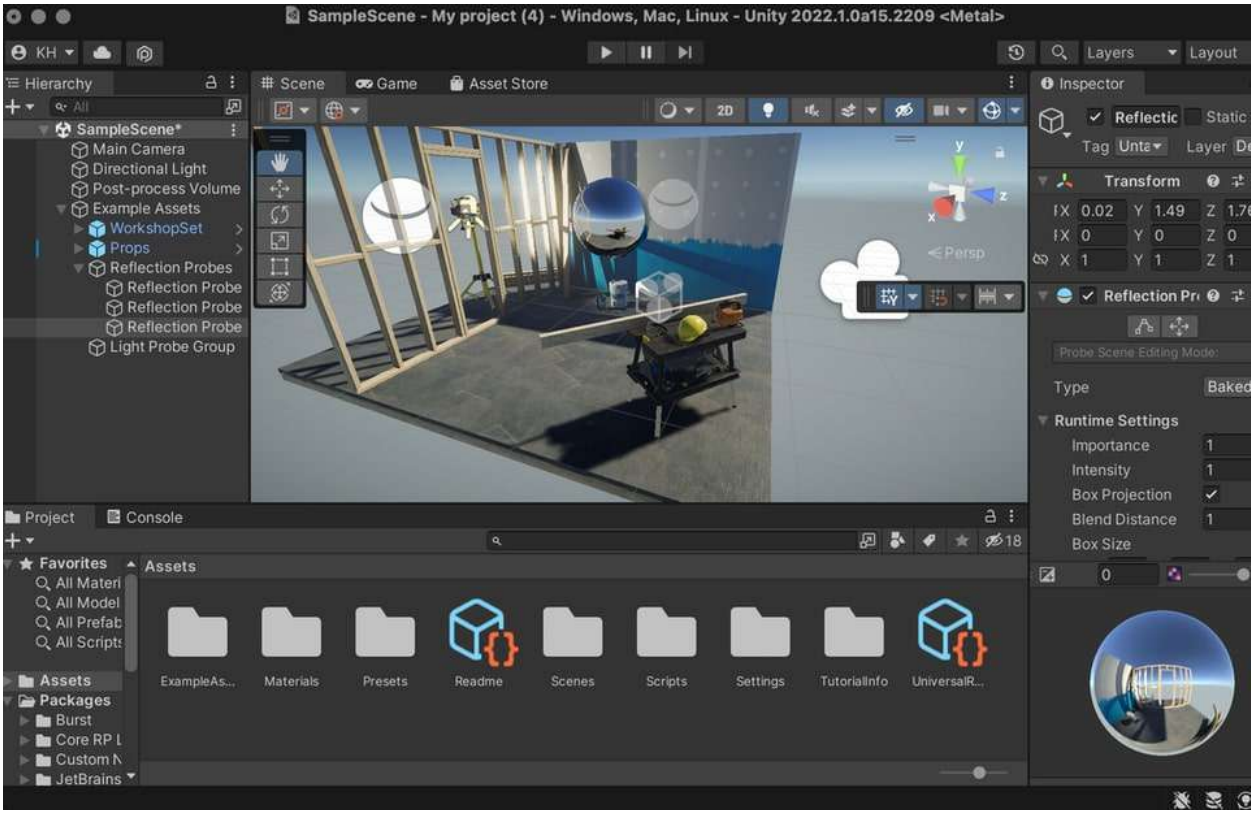


Figure 4.2: The editor of the Unity game engine.

Unity supports scripting with C# language, for implementing an application with interactive functionalities.

Scripting is an essential ingredient for building interactive applications with Unity. Applications need scripts to acquire the input from the player, to apply functionalities and to arrange events in the gameplay. Beyond that, scripts can be used to create graphical effects, control the physical behavior of objects or even implement a custom AI system for characters in the game[61]. In Unity scripting, the base class for all entities is called GameObject. Every GameObject can have a variety of components attached. They can have a mesh to define its actual physical shape, a mesh renderer to apply materials and lighting to an object, physics components like rigidbody and colliders that simulates things like gravity and collisions in the real world. Furthermore, in order for the users to go beyond the existing functionalities, they can attach their own C scripts on a GameObject by creating new components for introducing custom behavior like receiving hit points when a character runs into an enemy. In this way, users can trigger game events, modify component properties over time, respond to user input in any desired way[61], or to even manage other GameObject's components or states. To achieve this, Unity supports the C# programming language natively. C (pronounced C-sharp) is an industry-standard Object-Oriented Programming language similar to Java or C++. It is a general-purpose, multi-paradigm programming language encompassing strong typing, lexically scoped, imperative, declarative, functional, generic, object-oriented (class-based), and component-oriented programming disciplines. It was developed around 2000 by Microsoft as part of its .NET initiative, and later approved as an international standard by Ecma (ECMA-334) and ISO (ISO/IEC 23270:2018). C# was designed originally by Anders Hejlsberg, and its development team is currently led by Mads Torgersen [66].

4.2.2 Unity Assets

Users can create and sell their own assets to other game developers through the Unity Asset Store. In this store users can find from 2D and 3D assets to even whole environments to enrich their games. Furthermore, there are packages of libraries that can contain custom scripts offering a specific functionality or mechanism. Unity Asset Store launched in 2010. By 2018, there had been approximately 40 million downloads through the digital store[73]. Below we mention the assets that were downloaded through the Unity Asset Store during the development of our VE and our interaction mechanics, followed by a short description:

- **SteamVR Plugin (2.7.3)**: Valve maintains a Unity plugin to smoothly interface SteamVR with Unity. With SteamVR developers can target one API that all the popular VR headsets can connect to. The modern SteamVR Unity Plugin manages three main things for developers: loading 3d models for VR controllers, handling input from those controllers, and estimating what the hand looks like while using those controllers. On top of managing those things, they have an Interaction System example to help get the development of VR applications off the ground, providing concrete examples of interacting with the virtual world and their APIs[62]. This was the library that all the interaction mechanics were built upon, by extending what was already offered with custom functionality through scripting.

- **ProBuilder**[6]: It is a hybrid tool for 3D modeling and level design. It is optimized for building simple geometry, but capable of detailed editing and UV unwrapping too. It used to be available for download through the Unity Asset Store, but Unity acquired it in 2018, so it is part of Unity now. ProBuilder is used to quickly prototype structures, complex terrain features, vehicles and weapons, or to make custom collision geometry, trigger zones, or nav meshes. Many games and VR experiences made with Unity feature ProBuilder modeling and level designs. In our experiment, it was used for the creation of the map.

- **Plants**[7]: A package that contains 3D models of different plants along with their assets. It was used to decorate the map with assets that creates a calm feeling to the users.

- **Free Trees**[8]: A package that contains 3D models of different kinds of trees. Just like the plants, this package was used to decorate the map. From this package, we chose to use only Palm trees.

[6] https://unity.com/features/probuilder

[7] https://assetstore.unity.com/packages/3d/vegetation/plants/plants-150261

[8] https://assetstore.unity.com/packages/3d/vegetation/trees/free-trees-103208

- **AllSkyFree**[9]: This package contains 10 skies to set to the environment. Unity has the skybox property in order to change the sky of the game. In our experiment, we avoided setting a roof to the map in order to avoid creating feelings of claustrophobia to the users. So, we set a cloudy-blue sky to the VE.

4.2.3 Visual Studio

Visual Studio is an integrated development environment(IDE) from Microsoft. It is used to develop computer programs, as well as websites, web apps, web services and mobile apps. It uses Microsoft software development platforms such as Windows API, Windows Forms, Windows Presentation Foundation, Windows Store and Microsoft Silverlight. It can produce both native code and managed code.

Visual Studio includes a code editor supporting IntelliSense (the code completion component) as well as code refactoring. The integrated debugger works both as a source-level debugger and a machine-level debugger. Other built-in tools include a code profiler, designer for building GUI applications, web designer, class designer, and database schema designer. It accepts plug-ins that expand the functionality at almost every level—including adding support for source control systems (like Subversion and Git) and adding new toolsets like editors and visual designers for domain-specific languages or toolsets for other aspects of the software development lifecycle (like the Azure DevOps client: Team Explorer).

Unity is configured to use Visual Studio as the default external script editor. By downloading all the necessary libraries, it allows the easy development of new functionalities. When a change is made to a script, Unity automatically compiles the code, checks for errors, and loads the changes. Also, it loads all the required libraries, so it is able to predict and suggest corrections using the IntelliSence. Therefore, it is suitable for game development with Unity. The default interface of Visual Studio can be seen at 4.3

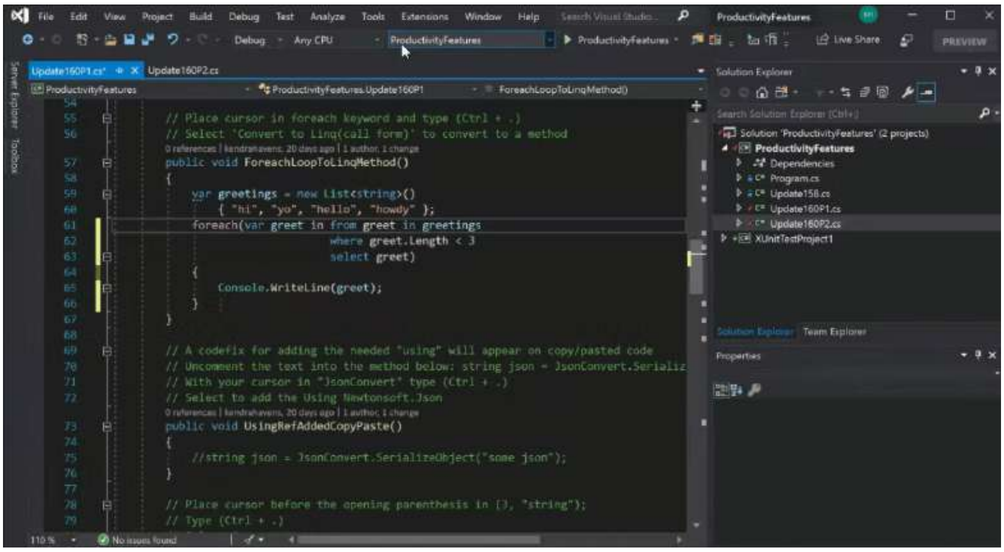


Figure 4.3: An example of the default interface of Visual Studio.

[9] https://assetstore.unity.com/packages/2d/textures-materials/sky/allsky-free-10-sky-skybox-set-146014

5. STUDY

As it is already mentioned, in this study we evaluate the effects of different direction sources in CAL in terms of motion sickness, performance, preference and presence. To achieve this, we designed an experiment in order to examine the effects of each direction source on these aspects of the user experience. During the design process, we focused on the way that the experiment would be organized, the procedure of the experiment, which data will be valuable for us to gather, and how we would reach conclusions with fair and transparent results. The gathered data that we chose to collect are divided into the objective data, which are mainly gathered by measurements inside the VE, and some subjective data, which are related by the user's point of view, and they are assessed using mixed methods approach of data collection through questionnaires and a concluding interview, at the end of each experiment.

Therefore, in this chapter, we present the collected data for the objective measurements, the questionnaires we used for the subjective measurements, and lastly some information about the participants and the procedure we followed.

5.1 Data Logging

Ideally, while conducting an experiment, we would like to collect as much data as possible that will allow us to support the outcomes of the evaluation on our targeted axes and also, to be able to analyze the users' performance and behavior in the experiment afterwards. Consequently, the virtual experience that we implemented records some objective data based on the user's actions and behaviors. We characterize these data as raw data. Moreover, among these data are answers that the users submits in immersed questionnaires, as we are going to explain in the next section in more detail.

When a participant completes the experiment, the gathered data is recorded from the application into a JSON[**?**] file. The name of this file is structured as:

`XX_L_YYYY_MM_DD_HH_mm_ss.json`

- `XX`: Stands for a unique increment id for each experiment.
- `L`: Stands for the row id of the Latin Square Matrix, which is going to be described in the next section.
- `YYYY_MM_DD_HH_mm_ss`: The timestamp that the experiment started.

Specifically, we store data related with the performance and the behavior of the users for the total experiment, for each one of the methods and for every task using each method. For all of these we store the duration in seconds, and the timestamps about when it started and when it was completed. For each user experiment we store some additional information like the experiment id and for each method, we also keep some statistics about the controllers usage and the preferred hand (right or left). For all the tasks that the users perform, we collect the trajectories of the users, meaning a list of positions in the map along with a timestamp for each position. A new trajectory is added in this list when the user moves a distance greater than a constant value. With this list we can recreate the path that the users moved while performing the specific task with a method, and also we can calculate the velocity. In addition, for each task we store specific data related to the exact task. In the zigzag task we collect the times that the user moved out the path, the duration in seconds that the user was out of the path, a list with timestamps that shows when the user got out and in the path and the accuracy of the user. The accuracy is calculated by the following formula:

$$accuracy = \frac{duration - outDuration}{duration}$$

Specifically, it is calculated as the division of the duration that the user was inside the path over the total duration.

In the corridor task, we keep the amount of the dots that the users counted in order to evaluate their accuracy, and in the color game an array that contains information about where each cube was spawned, when it was grabbed, when it was placed and who was its type.

All these data are stored in the JSON file that is created at the end of the experiment by the application. In order to better analyze some of them, we had to organize them in a CSV. For these reasons, a Python script was made.

Furthermore, we decided to record the whole experiment for each user, in a way that the user's behaviors in the real world and in the virtual, can be seen simultaneously. In this way, we can obtain useful information through observation by ”re-watching” the experiment. In addition, with this way, we keep all the comments, notices and reactions of the users, in order to be evaluated later. For the screen capturing, we utilized the OBS which is a free and open source software for video recording and live-streaming. The capturing of the real world is made by a WebCamera, and the capturing of the virtual world by screen recording. The real world is placed in a box at the bottom right, and the rest of the frame is from the computer. Also, the sounds are recorded by the camera's microphone. An example frame from the video capture can be seen at Figure 5.1.

5.2 Questionnaires

5.2.1 Pre-Study

Before we started the experiment, we asked the users some questions in order to better understand their profile. Some of these questions had Likert style scaling for answers, and some others were open. These questions among with their available answers can be seen at Table 5.1

For keeping and storing the answers of the users, we created an online form using Google Forms. So, while the users were answering, a member of our team was filling out this form.

5.2.2 Immersed Questionnaires

To approach the axes of presence, preference and motion sickness, we utilized multiple questionnaires. Those related with usability and presence took place immersed inside the VE by utilizing the input-panels. In this way, when the users completed all the parts with a method, they evaluated the current method virtually before moving on. Their answers

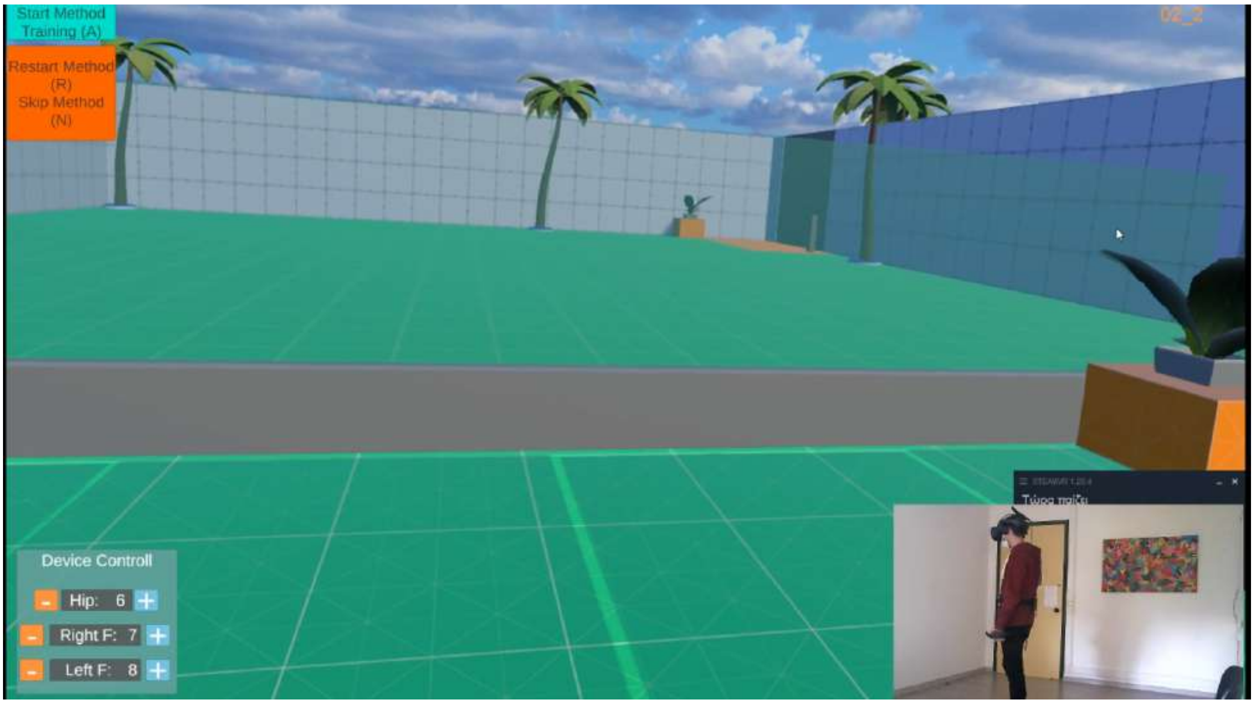


Figure 5.1: Example of a frame from the video capture.

were stored in the json file that was mentioned in the Data Logging section. The advantage of the immersed questionnaires is that the users are able to test and check the method while they evaluate it [54]. The scale of the answers were in a five-point Likert type. The users could select the answer that describes best how they felt. The options can be found below:

- None
- Slight
- Moderate
- Fairly
- Severe

Most of the questions were picked from the Presence Questionnaire (PQ) [65], and a question about usability was picked from the USE Questionnaire[42]. The questions and their origin can be seen at the Table 5.2.

5.2.3 Motion Sickness Questionnaires

The questionnaire about motion sickness took place after the immersed questionnaire. When the users completed all the parts and the immersed questionnaires with the current method, they were asked to take a break before moving to the next method. That break was planned in order to make the users relax and to reset their fatigue and dizziness that could have been induced by the method, before moving to the next one. Despite the fact that this break leads to breaks in presence, we thought that it was necessary in order for the users to get some rest before continuing with the next method and restore their initial

Table 5.1: The Post Study Questionnaire

Question ID	Question	Answers
PS1	How do you define your gender?	Open
PS2	Which is your experience with VR?	0, 1-3, 4-10, 10+
PS3	How many of them were with CAL?	None, some of them, half of them, the most, all of them
PS4	Do you have any experience related to sports, dancing or martial arts?	Open
PS5	Do you have any experience with video games? If yes, what kind?	Open
PS6	How often do you use a thumb-stick while playing video games?	None, some of them, half of them, the most, all of them
PS7	What is your familiarity with systems that detect body movements, such as: Wii-Playstation Move, Kinect, Motion Capture	0, 1-3, 4-10, 10+
PS8	Do you feel well?	Open

state as much as possible and avoid any effects to be transferred from one method to the next. Moreover, in this break, they answered the questions of the motion sickness questionnaires. So, the users removed their headset, sat for a couple of minutes and answered some questions about how they feel. We looked for common symptoms that can appear in each method. The most common questionnaires about motion sickness are the MSQ[29], SSQ[33][1] and also the VRSQ[**?**] and CSQ which are more specialized in VR. MSQ is a questionnaire that was created to measure the sickness that is created to the passenger on a moving vehicle. However, since the feeling of sickness is the same in VR it is also used for the motion sickness that is introduced by the VR. In an attempt to

[1] https://www.researchgate.net/figure/Simulator-sickness-questionnaire_fig3_324487892

Table 5.2: The questions asked in the Immersed Questionnaires

Question ID	Question	Question Origin
IQ1	How much were you able to control your movement?	PQ-1
IQ2	How natural was the mechanism which controlled movement through the environment?	PQ-5
IQ3	How easily could you move in the virtual environment?	PQ-10
IQ4	How much did your movement in the virtual environment seem consistent with the real world movement?	PQ-7
IQ5	How quickly did you adjust to the mechanism which controlled movement in the virtual environment?	PQ-20
IQ6	How difficult was it for you to concentrate on the assigned tasks or required activities rather than on the mechanisms which controlled movement?	PQ-22
IQ7	How fun was it to use this method?	USE-26

make it more specialized in simulators, the US Army created the SSQ, which is a subset of the MSQ. SSQ is the most commonly used questionnaire for measuring the sickness in VR[33]. Recently, an attempt was made to design a questionnaire that will focus on motion sickness created by VR. In this way, the VRSQ and CSQ were made. They are subsets of SSQ, but they were not tested in many other studies in order to examine their effectiveness, so we avoided using them.

Therefore, for the evaluation of the motion sickness, we selected specific symptoms from the SSQ which we believed that are the most related in our context. The answers were a four-point Likert scale, in which the users should select the one that describes their feeling the best. Each answer was mapped in a weight value for the analysis process. The available answers were:

- None | weight: 0
- Slight | weight: 1
- Moderate | weight: 2
- Severe | weight: 3

For the collection of the motion-sickness answers, we created a Google Form in which we stored the answers from the users as we asked them. The symptoms that we asked for are shown in the Table 5.3.

Table 5.3: The symptoms that asked for the Motion Sickness Questionnaires

Question ID	Symptom
MSQ1	General discomfort
MSQ2	Fatigue
MSQ3	Headache
MSQ4	Eye strain
MSQ5	Salivation increasing
MSQ6	Sweating
MSQ7	Nausea
MSQ8	Dizziness

Table 5.4: The questions in the Post-Study Questionnaires

Question ID	Question
AS1	Which method was the easiest to use?
AS2	Which method do you think was more effective?
AS3	Which method felt more natural (more related to the real world)? Why?
AS4	Which method made you pay attention to the real world and why?
AS5	Which method was your favorite?

5.2.4 Post-Study

At the end of the experiment, when the users completed all the tasks for all the methods and answered all the questionnaires, the virtual experience was over. Then, they answered questions about all the methods comparatively. In this phase we asked questions about the user's preference and which method generated the highest sense of presence to them. The questions that we asked in this phase are shown in the Table 5.4:

These questions were asked in the context of an open interview. We asked the post-study questions, and we encouraged the users to tell us not only their preferences but also extra comments and details. These interviews were recorded with a mobile phone, in order to be analyzed later.

5.3 Participants and Procedure

The total duration of the experiment was about an hour, and the experiment took place at the Department of Informatics and Telecommunications of the University of Athens. For the VR experience, we created a play area with a size of 3x3 square meters, providing plenty of space for the users to feel safe and comfortable to move around. In total, 24 users participated. However, 2 of them were not able to complete the study due to discomfort, so they stopped. Their data were not included in the final analysis. Moreover, in most cases, the experiment flow was not interrupted, unless there was an important reason for that. Since the experiment took place in Greece, and the participants were all Greek, all informational material and guides in the VE were translated into Greek, so they would be easily understandable and to avoid unnecessary confusions. As the experiment was conducted in the midst of the COVID-19 pandemic, we took all required precautions to ensure the safety of the participant and conductors. We left a 2-hour gap in between different sessions to have ample time to prepare before the next participant comes and to apply all the necessary procedures according to the COVID-19 health protocols of the time.

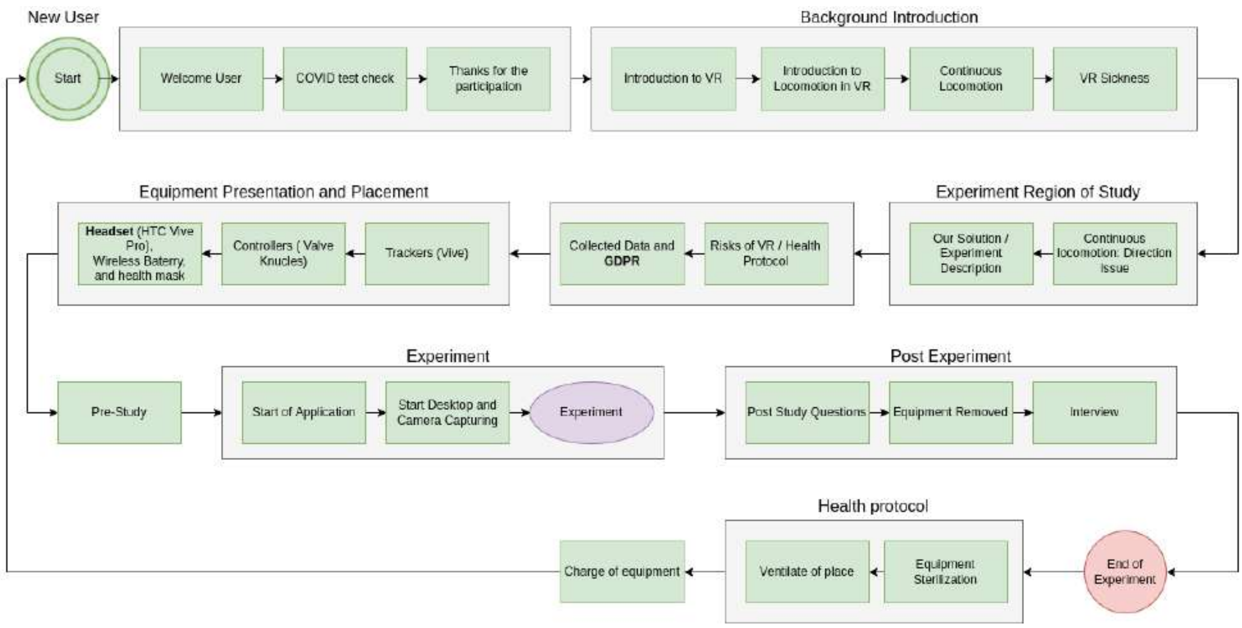


Figure 5.2: The procedure of the whole experiment.

The procedure of the experiment, upon arrival of the participant, was divided in the phases below:

- **Welcome Phase**: At first, a member of our team welcomed the participant, checked if they had all the necessary documents related to COVID-19, we thanked them for their participation, and we offered them some refreshments.
- **Background Introduction**: Then, a brief introduction was made related to the nature of VR as well as its goals, and after that, we informed them about locomotion in VR and motion sickness.
- **Brief Background of Study**: Next, we explain to them the field of studies of this experiment. More specifically about the CAL and the direction issue. In addition, we

explained in detail the different direction methods that we have developed, so the participants are informed about them.

- **Bureaucracy Phase**: In this phase, we also informed the participants about necessary precautions of COVID-19 that we follow and about the Risks of VR. Moreover, we provided the participant with an experiment information sheet and a consent form (Appendix C).

- **Pre-Study**: Then, we continue with the pre-study questionnaire, in order to better understand the profile of the participants, their familiarity with VR, and with technologies related to our experiment.

- **Equipment Presentation and Placement**: Afterwards, the equipment presentation to the participants and the placement on them follows. Firstly, we place the trackers, then we give the controllers, and we help them to wear them on their hands, and then the VR headset. For the VR headset, the participants firstly wear a protection mask, in order to not come in contact with it, and then they wear the device. Since our device is tetherless, we hung the battery from the belt that the tracker of the hip has. Then, we are ready with the equipment, so we can proceed to the experiment.

- **Experiment**: In this phase, we start the experiment along with the video capture. At first, the participants start with the training scene, where they learn the basic mechanics of the application, and then proceed to the experiment scene. There, the application picks the first method from the Latin Square matrix. When the participant completes all the tasks with the current method and answers the immersed questionnaires, follows the break in which we ask them the motion sickness questionnaires. After that, the participant wears the VR again to proceed to the next method. This procedure is repeated for all the four parts of the experiment. A diagram of that flow can be seen at Figure 5.3

- **Post Experiment**: After the participants have completed all the parts with all the methods, the VR experiment is over. The participants remove the headset and sit to relax. In this phase, we ask them comparative questions about all the methods and their opinion, while recording them. In the end, we remove the equipment, and we say goodbye to the participant. At this point the experiment is completed, so we stop the video recording too.

- **Conclusion**: After the participant leaves, we did some preparation to welcome the next participant. We sterilized the equipment, ventilated the experiment-room, and charged the devices (controllers, trackers and headset's battery). The experiments were scheduled every two hours in order to have plenty of available time between each experiment.

The complete procedure of the experiment can be seen in Figure 5.2.

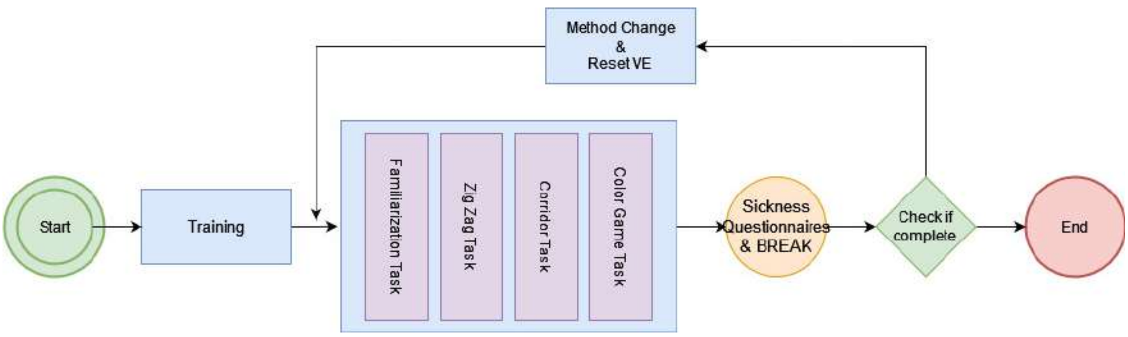


Figure 5.3: The flow of the experiment

6. ANALYSIS

This chapter presents the characteristics of the participants that took part in the experiment and the results of the statistical analysis from the logged data and the questionnaires. In each case, the analysis approach is briefly described, followed by the main findings. First, the participants' characteristics are shown according to the collected data from the pre-study. Then, the logged data are examined for each method in each part, and then follows the results from the immersed and motion sickness related questionnaires. After that, the comparison results are followed from the post-study questions along with the findings from the users' interviews. Last, some observation findings are presented that were noticed. For the data manipulation, analysis and visualization, multiple Python scripts were implemented.

6.1 Participants Characteristics

In the experiment, 24 users participated in total, and two of them were not able to complete it due to intense discomfort. The collected data of these two cases were ignored in the following analysis. In the question PS1, 62.5% of the users said they define their gender as male, and the rest 37.5% as a woman. Of them, 75% answered that they have some experience in playing video games on the PS2 and 83% had experience related to sports. About their experience in VR and continuous locomotion, over half of the users had used VR 1-3 times and most of them answered that none of them was with continuous locomotion. The exact percentages are shown in the charts in Figure 6.1.

In the PS6 about the usage of thumb sticks, the most common answer was "most of the time", at 29.2% and in the PS7 most of the users had no familiarity with systems that detect the body of the users. The results in more detail are shown in the Figure 6.1. In the last question (PS8), about how the users feel before starting the experiment, all the users answered that they feel fine.

6.2 Performance data

In this section, we analyze the performance data that are generated by the application, after each user completed the experiment. These are the objective data that were discussed in the Study section, and they are stored in a JSON file. With this data we calculate the performance of the users in each part with every method, and also we use them to extract derived data just like velocity.

6.2.1 Logged Data Results

By the raw data that was logged in the JSON file, we find the mean duration of the immersed experiment session was 2422.6 seconds (about 40 minutes), having the fastest execution at 1834 seconds (about 30.5 minutes) and the slowest at 3000.6 seconds (about 50.1 minutes). The mean duration with each method from all the users is shown in the Figure 6.2, along with the highest and lowest values, which are visualized with a black vertical line.

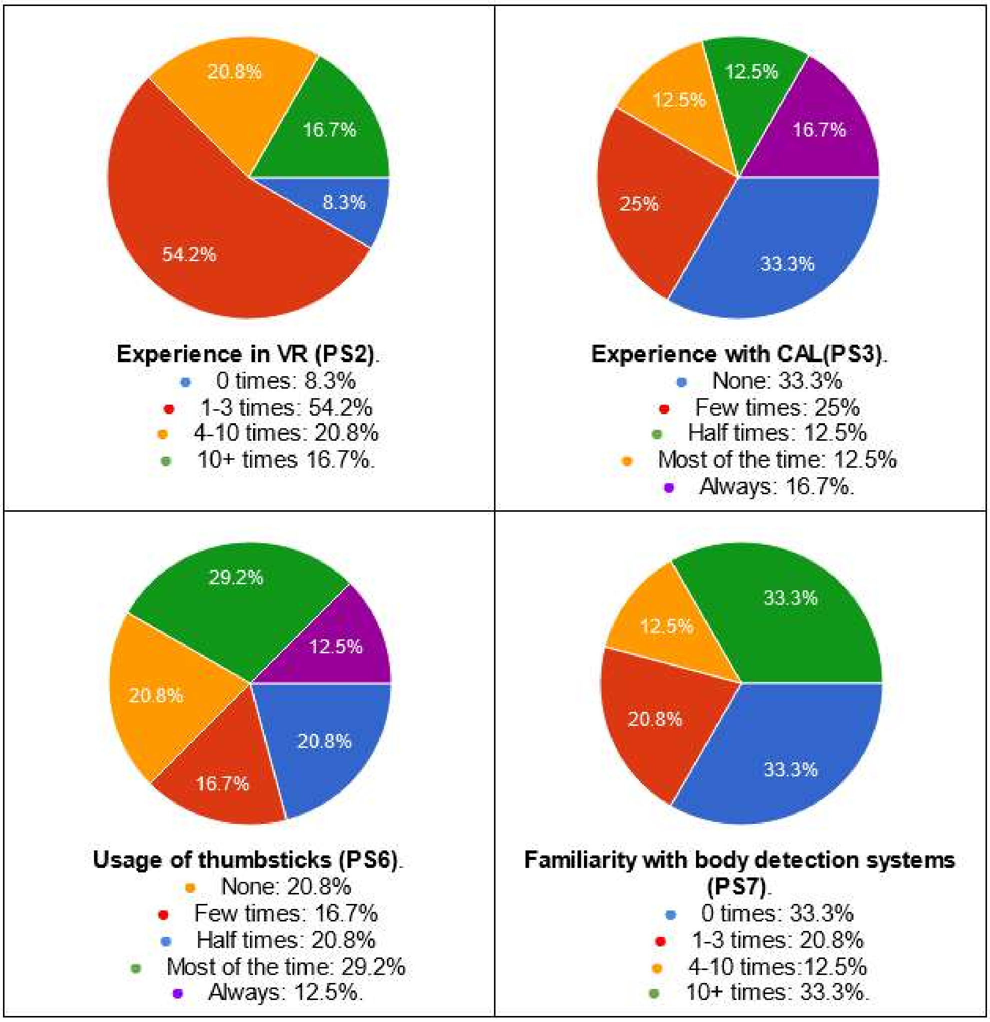


Figure 6.1: User characteristics according to the results of the Pre-Study

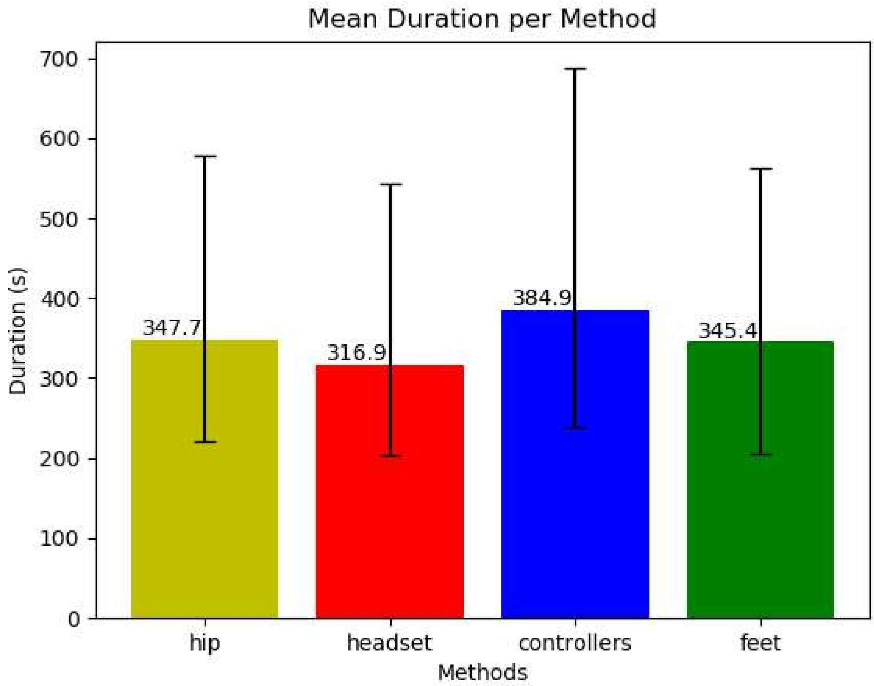


Figure 6.2: Mean duration of the users with each method.

As we can see, the fastest performances were done with the Headset method and the slowest with the Controller method. Similar behaviors show the maximum and minimum performances. About the Hip and the Feet methods, there are no significant differences in performance, having the Feet method slightly faster.

The Figure 6.3 shows the mean duration of the users in each part with every method. In this chart, there are also the fastest and slowest performances.

From the Figure 6.3 we can see that in the zigzag task, there is not a significant difference in duration for each method. Similar behaviors can be seen also in the next two tasks (corrido and color game), with a minor head start in the Headset method, with which users had a slightly better performance.

As is already mentioned, in the zigzag part the users were asked to follow the path on the floor and to try to stay inside it as much as they could. The mean amount that users got out of that path with each method can be seen in Figure 6.4.

The method that made the user get out of the path was the Feet-based one. This follows the Headset method, and the Controller method is the one that led them to lose the path most of the time. The duration that the users got themselves out of the path can be seen in the Figure 6.5

The Figure 6.5 reveals that the Headset method makes the user stay out of the path most of the time, and then follows the Controller method. Hip-based method was the one that kept the users the least time out of the path. Therefore, in total, with the Hip-based method, the users had the best accuracy, as can be seen in the Figure 6.6.

Despite the lowest rate of the Headset method in accuracy, it is worth mentioning that the Headset method was the one that had the most users to achieve 100% accuracy. On the other hand, the method with fewer users to execute the zigzag perfectly was the method with the Controllers. In more detail, the Table 6.1 shows the number of users that achieve

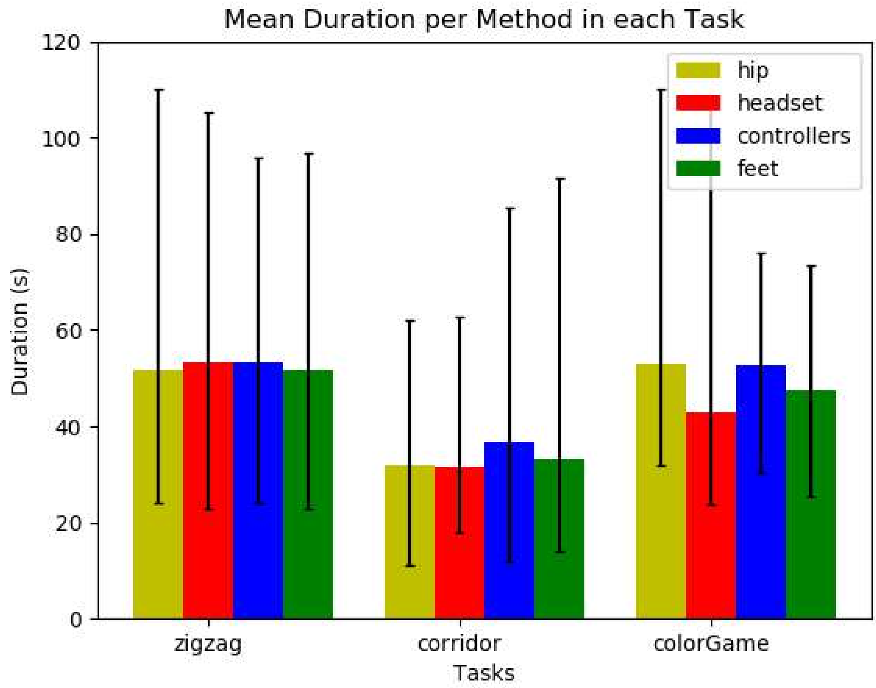


Figure 6.3: Mean duration of the users with each method in each task.

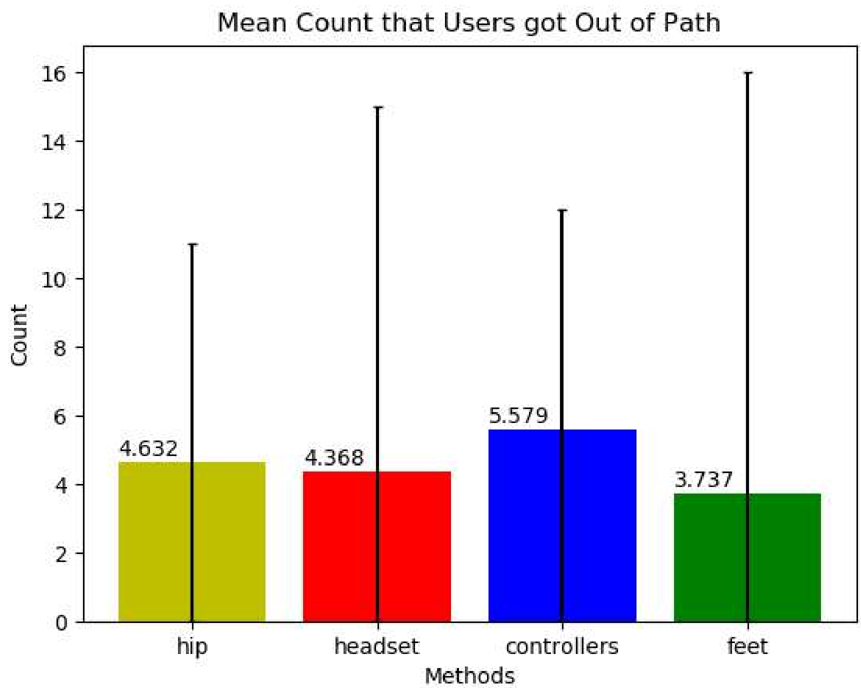


Figure 6.4: Mean amount that users got out of path with each method in ZigZag

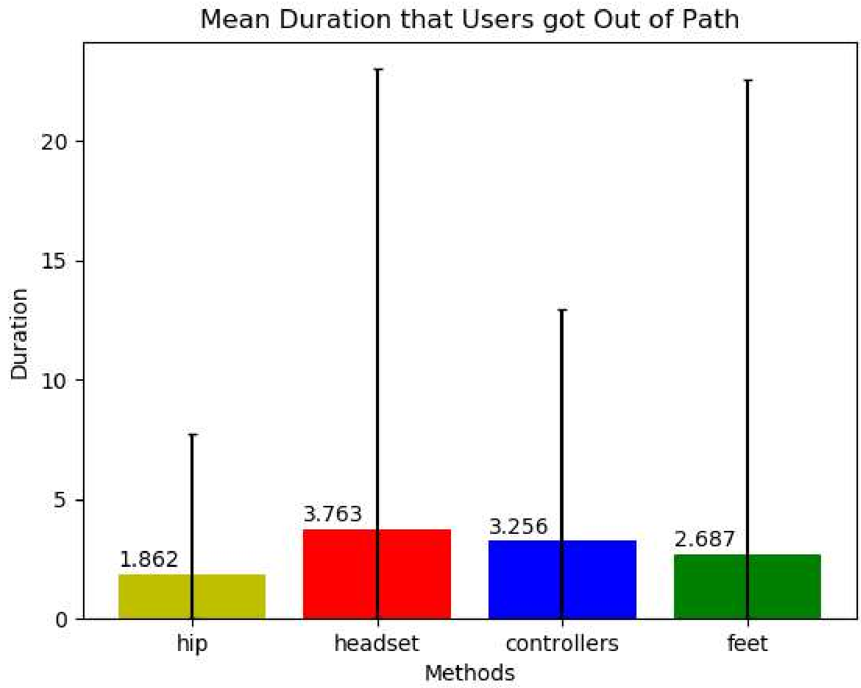


Figure 6.5: Mean duration that users stayed out of path with each method in ZigZag

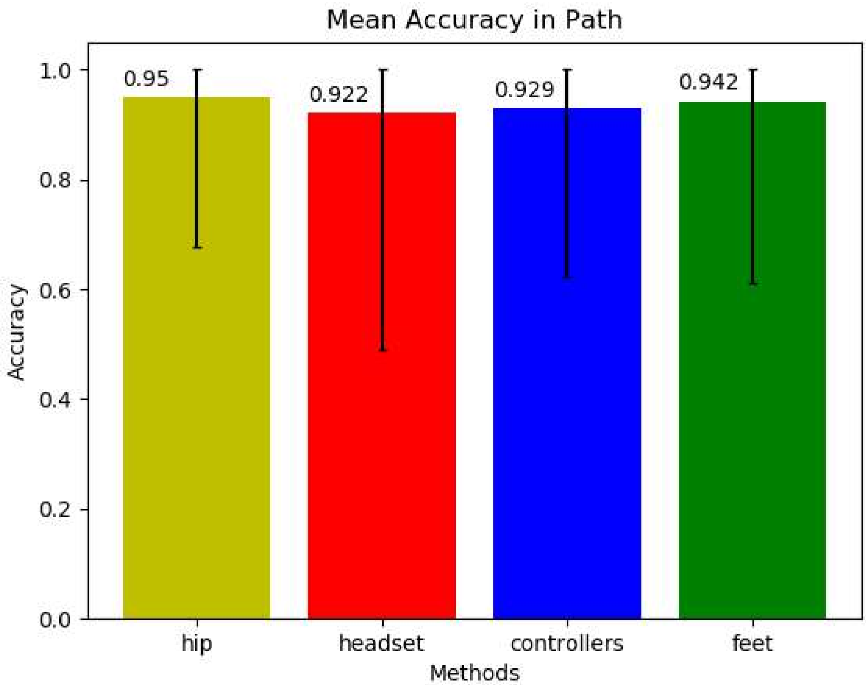


Figure 6.6: Mean accuracy of users in path with each method in ZigZag

Table 6.1: Number of users that achieve 100% accuracy with each method in the ZigZag task.

HIP	3
HEADSET	6
CONTROLLERS	1
FEET	4

100% accuracy with each method.

About the dot counting task in the corridor part, to calculate the error of the users with each method we applied the formula below:

$$error = \frac{existedDots - countedDots}{existedDots}$$

The results of this formula can be seen in Figure 6.7.

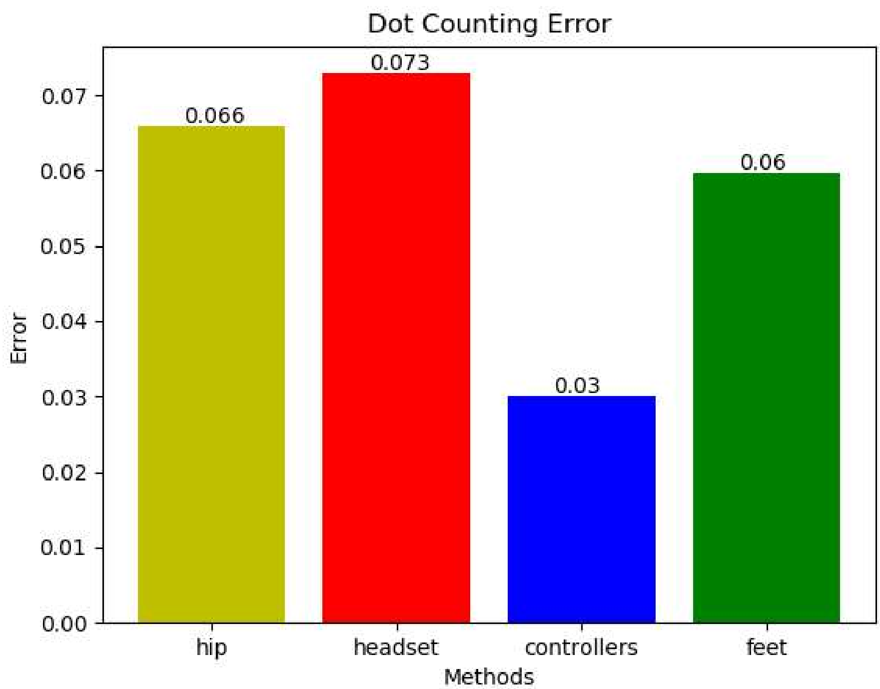


Figure 6.7: Mean error in dot counting with each method.

The Figure 6.7 shows that the error is greater with the Headset method and the least with the Controller method. This chart proves that because the Headset-based method makes the users move towards where they look, this inflexibility restricts users' ability to look around freely. Consequently, it reduces visual observation, leading them to miscount the dots at a higher rate. This is also because the corridor task requires the users to look at both sides of the corridor as they walk it through. Thus, in such a task, direction sources that allow the users to look around freely, have advantages.

6.2.2 Trail Visualization

As it is mentioned in the Study section, in the logged data, the application stores the trajectories of the users in each part with every method. In this way, by placing the trajectories as points in the VE, and connecting them, we can recreate the path that each user followed. By placing all the participants' paths with each method on the map we create some trail visualization that displays the most popular paths that are followed by the users for each method. These heatmaps are shown in Figure 6.8 for each method.

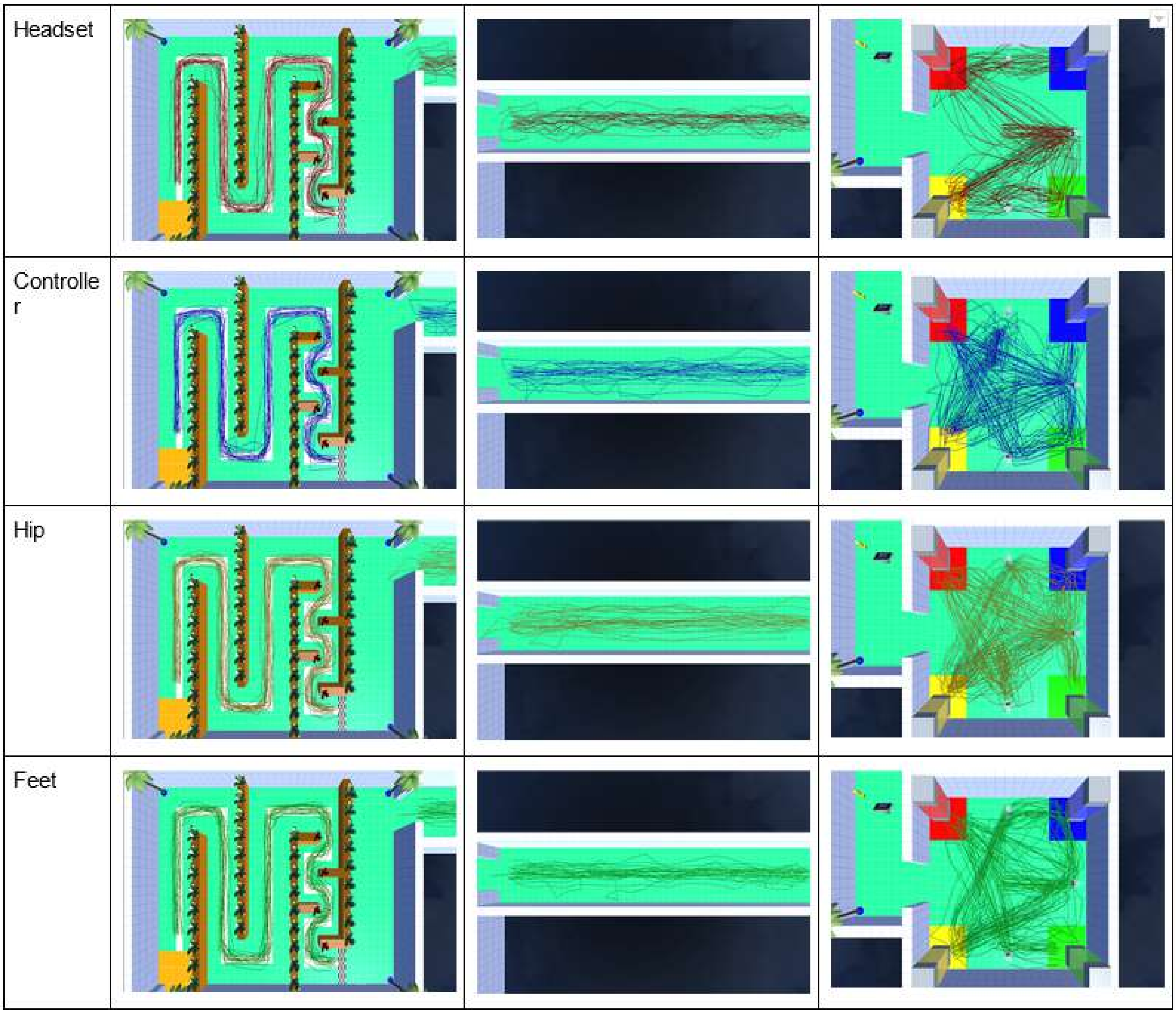


Figure 6.8: Trail Visualization for each method.

In the zigzag part, as we can see from the first column of the trail visualization, most of the users seem to follow the path strictly. However, few users have lost the path completely for a long distance. These cases are more often in the Headset method, which explains the lower scores in accuracy that we reported previously. Furthermore, in the last turns in this part, many users avoided taking the sharp turns, and they preferred to "cut" them, following a shorter path. This led to the loss of accuracy points. In the next part, most of the users follow a straight path. Specifically, in the Feet-based method, the majority of the users crossed the corridor following a common line without doing any turns, which led the trail visualizations to be intense in this line region. On the other hand, in the Headset method, we notice that the majority did not follow a straight line, as a result, the paths in the trail visualization are spread out with right and left turns. In the Controllers and the

Hip method, the user also moves in a straight line, without turning a lot just like in the Headset method, but they are not also as centered as it was in the Feet-based method. In the last part, there is not a lot to notice about the behavior of the users, since in this part the users moved freely from point to point. Therefore, the trail visualizations are more abstract. However, the intensity of the paths makes visible the order of spawners and capsules that the users visited in each method. Furthermore, in the Controller method, we can notice that the users' paths are spread out to the whole area. Therefore, the users avoided taking the shortest path from one place to the next. However, as we saw in the zigzag trail visualization, the users used to follow the shortest path, even when they had to follow a specific path. As a result, we can assume that this implies that these users did not have the control that they wanted using this method.

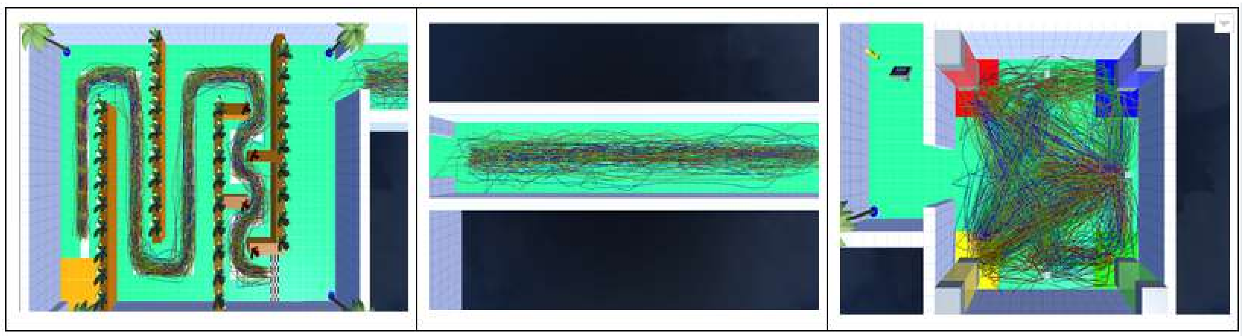


Figure 6.9: Trail Visualizations with all the methods.

In Figure 6.9 are placed all the paths from all the users with all the methods. These trail visualizations reveal that all the users followed the expected paths in the experience, without doing any unorthodox actions. Specifically, It is visible that in the zigzag part, all the users tried to follow the path with every method, in the corridor part, the majority of the users crossed it following a straight line, since the paths are centralized, and even in the color game the order of spawners and capsules for each method are still visible.

6.2.3 Derived Data Results

By processing logged data like trajectories, we can calculate and produce derived data about the user performance. Such data is velocity. Velocity can be calculated by the trajectories of the users, since along with the location, we log the timestamp. Therefore, by calculating the total distance the user traveled in a part and dividing by the duration in that part, we produce the mean velocity of the user in that part. Moreover, by calculating the delta time that it took a user to move from one location to another, we can calculate the velocity of the user at each point, and consequently how the velocity changed over the time in each part, with every method for all the users.

In Figure 6.10 is displayed the mean velocity of all the users in each task with every method.

As we can notice, there are no significant differences in velocity between the methods. In the corridor task, the Hip seems to stand out, giving the users the confidence to cross it faster while counting the dots. However, this may be related to the not-so-good scores in the dot counting with this method. Moreover, in the color game task, the users were faster with the Feet-based method.

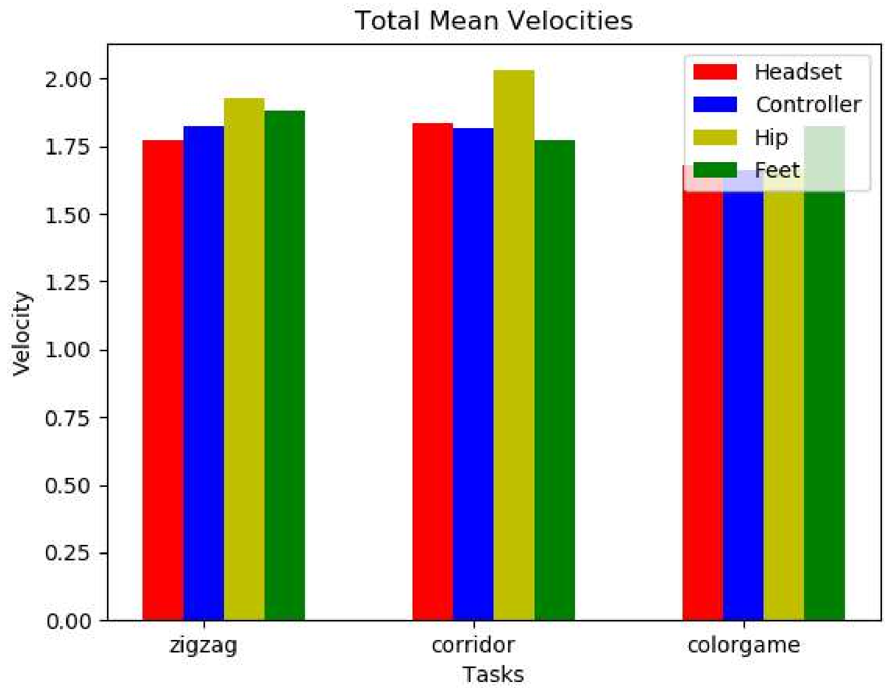


Figure 6.10: Mean velocity of users in each task with all the methods.

This behavior can be seen in multiple charts that show the velocity over the time of each user while executing a specific task. Some examples can be seen at Figure 6.11 Figure 6.12.

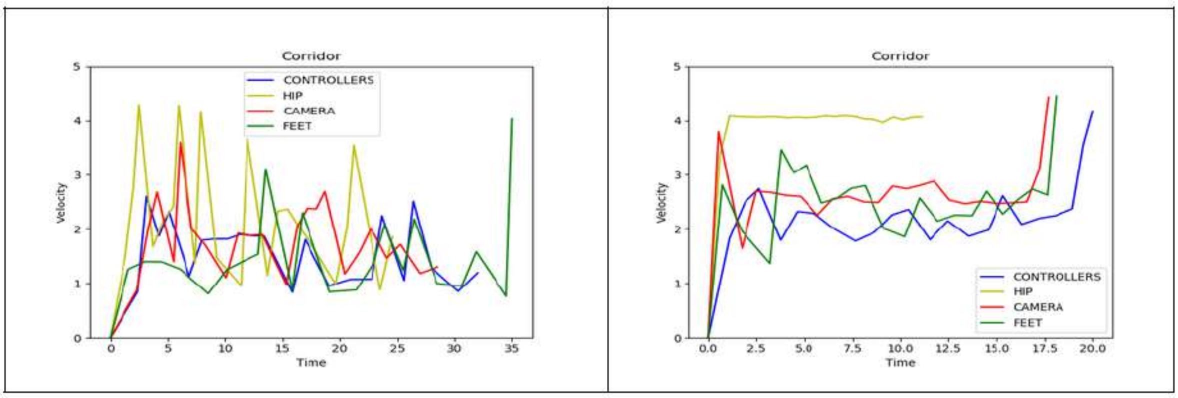


Figure 6.11: Velocity over time of two users in Corridor.

Most of the users navigate faster in the corridor task using the Hip-based direction source. As a result, some users can complete this task sooner with this method. This behavior is verified by the Figure 6.11.

Users move faster in the color game task with the Feet-based method. This behavior can be verified by the performances of two users that are shown in the Figure 6.12.

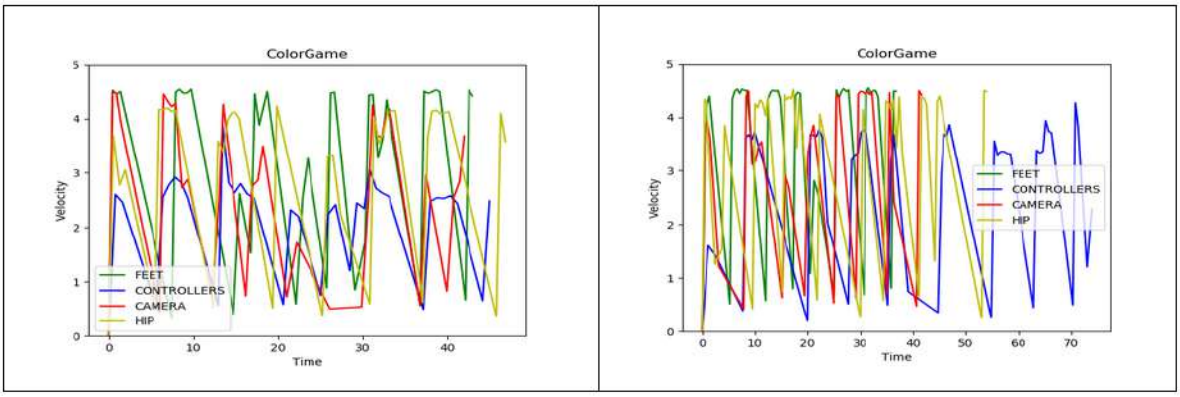


Figure 6.12: Velocity over time of two users in Color Game.

6.3 Questionnaire Results

In this section, we present the results of the different questionnaires that took part in our research. These collected data are subjective, so they describe the personal opinion of each user. First, the section starts with the immersed questionnaires, in which the users are asked about the usability of the method and the presence. Then, follows the results of motion sickness questionnaires and in the end the comparative questionnaires which the users answered about their preferences of methods.

6.4 Immersed Questionnaires Results

These questionnaires took part after the users completed all the tasks with a method, inside the VE, where they could test it while answering the questions. The question was displayed over an input panel and the users could select one of the available answers. The results can be seen in the Table 6.2. Because the IQ6 had a negative value, we had to invert the results for our analysis, to be aligned with the rest of the questions.

According to Table 6.2, the Hip and Feet methods as direction sources got the highest scores in the immersed questionnaires. In more detail, the users scored better with them when we asked about the control of the movement (IQ1), how natural the movement mechanism (IQ2), how easily they could move in the VE (IQ3) and how easily they concentrated in the assigned tasks instead of the movement mechanism (IQ6). Furthermore, they also got higher scores in the IQ7, which was about how much fun the method had.

Statistical analysis of results

For the analysis of the questionnaire questions, Friedman's nonparametric tests were used to firstly identify if there is any significant difference between the scores for the four methods (Headset, Controllers, Hip, Feet) that the users assigned to each question (on a 5-point Likert scale). The average score (AV) and standard deviation (STD) for each statement and each method have also been calculated and are shown at Table 6.2. Friedman's nonparametric tests revealed significant differences between the method scores in questions IQ2 and IQ4 Table 6.3.

The next step was to perform Wilcoxon pairwise comparison tests between the four methods for questions IQ2 and IQ4, to identify possible significant differences within each pair of methods. In the remainder of the section, we present the results, using Z to denote the

Table 6.2: Average and standard deviation for each method for the Immersed Questionnaires.

Question	Headset Method AV/STD	Controller Method AV/STD	Hip Method AV/STD	Feet Method AV/STD
IQ1-How much were you able to control your movement?	3.87 / 0.75	3.74 / 0.86	4 / 0.92	4.13 / 0.64
IQ2-How natural was the mechanism which controlled movement through the environment?	3.56 / 0.72	3 / 1	3.72 / 0.98	4.04 / 0.72
IQ3-How easily could you move in the virtual environment?	3.87 / 0.75	3.65 / 0.934	4.04 / 0.95	4.04 / 0.72
IQ4-How much did your movement in the virtual environment seem consistent with the real world movement?	3.47 / 0.73	2.47 / 1.03	3.45 / 1.1	3.95 / 0.72
IQ5-How quickly did you adjust to the mechanism which controlled movement in the virtual environment?	3.91 / 0.94	3.56 / 1.12	4 / 1.02	4.22 / 0.68
IQ6-How difficult was it for you to concentrate on the assigned tasks or required activities rather than on the mechanisms which controlled movement?	2.87(5-2.13) / 0.86	2.7(5-2.3) / 1.06	2.96(5-2.04) / 1.17	3.05(5-1.95) / 0.95
IQ7-How fun was it to use this method?	3.91 / 0.9	3.78 / 1.08	4 / 0.97	4.27 / 0.7
Total	3.63	3.27	3.74	3.96

Table 6.3: Immersive Questionnaire results summary: Friedman test results for the 7 questionnaire questions.

Question	Friedman test
IQ1-How much were you able to control your movement?	p=0.340/Chi-Square=3.358
IQ2-How natural was the mechanism which controlled movement through the environment?	p<0.001/Chi-Square=14.867
IQ3-How easily could you move in the virtual environment?	p=0.128/Chi-Square=5.691
IQ4-How much did your movement in the virtual environment seem consistent with the real world movement?	p<0.001/Chi-Square=20.869
IQ5-How quickly did you adjust to the mechanism which controlled movement in the virtual environment?	p=0.074/Chi-Square=6.939
IQ6-How difficult was it for you to concentrate on the assigned tasks or required activities rather than on the mechanisms which controlled movement?	p=0.599/Chi-Square=1.872
IQ7-How fun was it to use this method?	p=0.224/Chi-Square=4.375

Wilcoxon coefficient, which is presented unsigned, as the order of the results is shown in text, and p to denote the asymptotic significance. We set the significance level at 0.05. Table 6.4 summarizes the results, ordering the methods' average scores for each statement according to the detected significant differences.

From the results in Table 6.4 of the IQ2 we conclude that:

- The Controller-based method was picked as the least natural of the other methods.
- The Feet-based method was considered the most natural but also similar to the Hip.
- Since Hip and Headset methods do not have a significant difference, and Feet have with the Headset, we can conclude that the Feet-based method is considered the most natural in comparison with the rest, not just the Hip.

Similarly, for the IQ4 we conclude that:

- The Controller-based method was picked as the least consistent movement of all the others.
- The Feet-based method was considered more consistent than the one with the Headset.
- Since Headset and Hip methods do not have a significant difference, and Feet have with the Headset, we can conclude that the Feet-based method is considered the most consistent movement in comparison with the rest.

6.5 Motion Sickness Results

Motion sickness is one of the main axes that we investigate in our research. As it is mentioned, we asked the users about multiple motion sickness symptoms right after the users completed the immersed questionnaires. The users removed their headset and the rest of the equipment, sat in a chair to relax, and they answered questions related to their symptoms. The results of the questions were analyzed utilizing the weighted answers. The Table 6.6 contains the average weighted answer and the standard deviation from all the answers of the users in each symptom.

As we can see in Table 6.6, none of the symptoms appeared at a great level to the users, having the increased salivation symptom to not appear in any case.

In the Table 6.6, we present the average of the average values of the symptoms that were shown in the Table 6.6. In this way, we try to sum up the total motion sickness that each method induced in the users.

As we can see from the results at Table 6.6, none of the methods induce any major symptom, having the Hip-based method inducing the most motion sickness, and the least by the Headset method. The Feet and Controller methods did not have any significant difference.

Statistical analysis of results

As with the Immersed Questionnaires, we used Friedman's nonparametric tests to identify if there is any significant difference between the symptoms for our methods that the users

Table 6.4: Significant results of the Wilcoxon test for the pairwise comparison for the questions where significant difference has been detected in the Friedman test.

Question	Pair of methods	Wilcoxon parameters	Method Score Order
IQ2-How natural was the mechanism which controlled movement through the environment?	Headset-Controller	Z=2.415, p=0.016	Headset is more natural than Controller
IQ2-How natural was the mechanism which controlled movement through the environment?	Feet-Headset	Z=2.055, p=0.04	Feet is more natural than Headset
IQ2-How natural was the mechanism that controlled movement through the environment?	Feet-Controller	Z=3.113, p=0.002	Feet is more natural than Controllers
IQ4-How much did your movement in the virtual environment seem consistent with the real world movement?	Headset-Controller	Z=3.297, p=0.01	Headset is more consistent than Controller
IQ4-How much did your movement in the virtual environment seem consistent with the real world movement?	Feet-Headset	Z=1.897, p=0.058	Feet is more consistent than Headset
IQ4-How much did your movement in the virtual environment seem consistent with the real world movement?	Feet-Controller	Z=3.627, p=0.000	Feet is more consistent than Controller

Table 6.5: Average and standard deviation for each method for the motion sickness questionnaire.

Symptoms	Headset Method AV/STD	Controller Method AV/STD	Hip Method AV/STD	Feet Method AV/STD
MSQ1-General discomfort	0.318/0.477	0.41/0.5	0.545/0.963	0.318/0.646
MSQ2-Fatigue	0.0/0.0	0.09/0.29	0.182/0.501	0.182/0.395
MSQ3-Headache	0.136/0.351	0.45/0.21	0.091/0.294	0.0/0.0
MSQ4-Eye strain	0.045/0.213	0.45/0.21	0.227/0.528	0.0/0.0
MSQ5-Salivation increasing	0.0/0.0	0.0/0.0	0.0/0.0	0.0/0.0
MSQ6-Sweating	0.182/0.395	0.36/0.73	0.409/0.908	0.364/0.492
MSQ7-Nausea	0.182/0.395	0.38/0.47	0.318/0.568	0.318/0.646
MSQ8-Dizziness	0.273/0.55	0.32/0.57	0.364/0.902	0.318/0.477

Table 6.6: Average and standard deviation for each method for the motion sickness questionnaire.

Method	AV	STD
Headset	0.142	0.12
Controllers	0.199	0.168
Hip	0.267	0.178
Feet	0.188	0.164

Table 6.7: Motion Sickness Questionnaire results summary: Friedman test results for the 8 symptoms.

Symptoms	Friedman test
MSQ1-General discomfort	p=0.651
MSQ2-Fatigue	p=0.58
MSQ3-Headache	p=0.129
MSQ4-Eye strain	p=0.428
MSQ5-Salivation increasing	p=0.514
MSQ6-Sweating	p=0.718
MSQ7-Nausea	p=0.764
MSQ8-Dizziness	p=0.881

answered to each question (on a 4-point Likert scale). The average score (AV) and standard deviation (STD) for each statement and each method have also been calculated and are shown at Table 6.6.

Friedman's nonparametric tests do not reveal any significant differences between the method scores. The results can be seen at Table 6.7.

6.6 Comparative Results

The comparative questionnaire took part at the end of the experiment. The users had tested all the methods, and they were asked about their preference for each method over different topics. The Table 6.8 shows how many votes each method received in each question.

The results of this table are visualized in the Figure 6.13.

As we can see, the favorite method of the users according to the results in the table was the Headset, followed by a short difference in the Hip. The easiest to use method was also selecting the Headset and with equal votes the Hip and the Feet. As for the most natural method, also the participants chose the Headset method, and in second place follows the Feet method. Last, even though the Feet-based method was selected as the method that made the users pay the most attention to the real world, it was selected as the favorite method of the users. It is also worth mentioning that the Controllers method was selected the least in most of the questions.

As is already mentioned, we recorded the phase of the post-study, to better analyze the comments of the users. We encouraged them to explain in detail the reasons behind their picks. We analyzed these interviews and extracted the most common and repeated comments that the users highlighted, and also some others worth mentioning.

Table 6.8: Times that each method appeared in the results of the comparative questionnaires.

Question	Headset Method	Controller Method	Hip Method	Feet Method	None
AS1-Which method was the easiest to use?	12	3	11	9	1
AS2-Which method do you think was more effective?	11	4	9	9	1
AS3-Which method felt more natural (more related to the real world)? Why?	10	0	7	9	1
AS4-Which method made you pay attention to the real world and why?	1	3	4	7	11
AS5-Which method was your favorite?	7	1	7	11	1

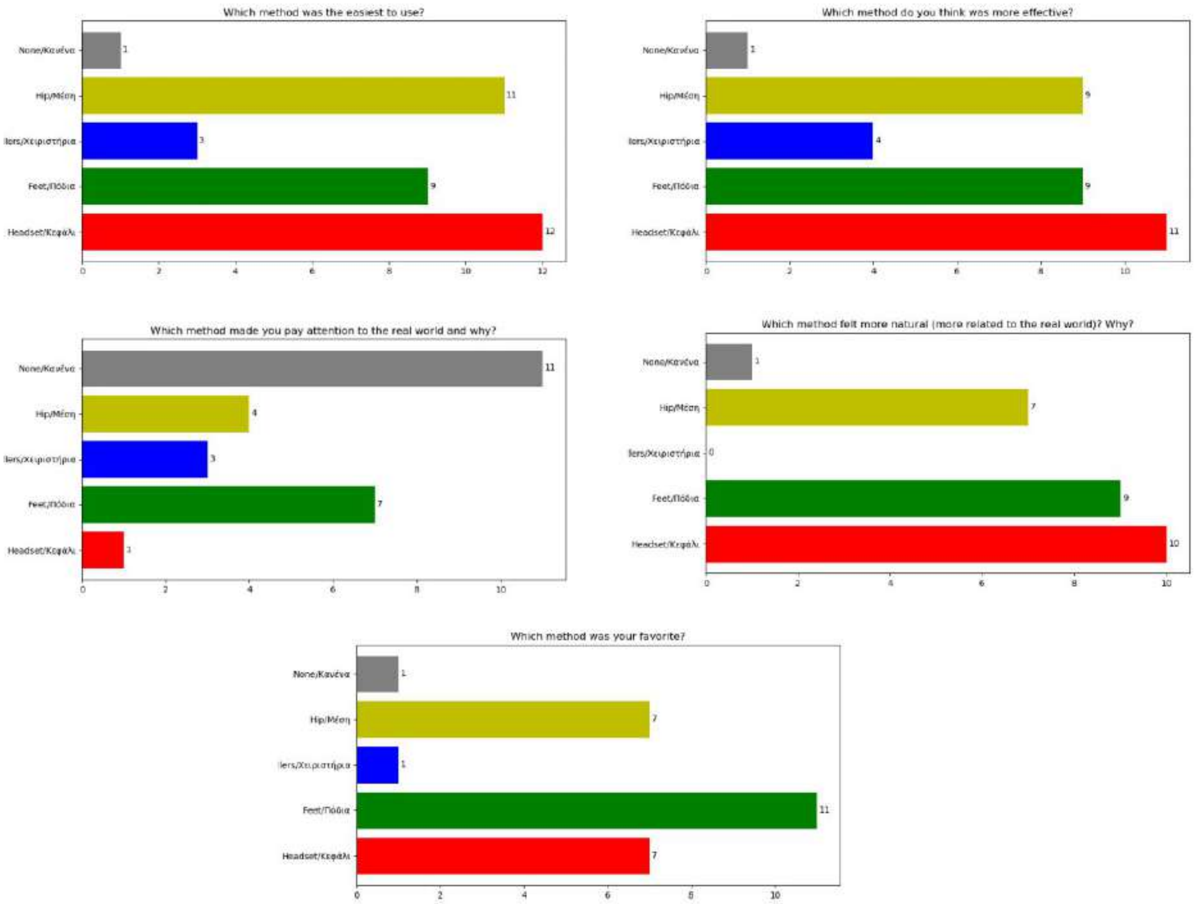


Figure 6.13: Charts with the results in Comparative Questionnaires.

In the AS1, eight users characterized the direction source based on the Headset as easy, and natural, and also mentioned that “it makes a lot of sense”. Means that the users used this method without providing a lot of effort. On the other hand, the Controller method was described a couple of times, as hard to use and unpredictable, which means that the users had a hard time using it. About the Hip- and Feet based, the answers did not differ much, having the users mentioned them as natural, relaxing, and also many of them mentioned that they were able to turn around by using their body, making it feel even more natural.

In the AS2, some users felt that they were the fastest with the Controller-based direction source, but Hip and Feet-based methods were more comfortable. In the question AS4 about which method made the users turn their attention in the real world, the users had a hard time answering since they could not clearly understand the question or to correlate it with a specific method. Many of them mentioned the Controller-based as the most unnatural because they had to keep in mind which direction their Controller points. Furthermore, some other users mentioned that they felt upset with the Hip-based method since they had to keep in mind where their body looks at, which was something that they were not used to. The Feet-based method led the users to move a lot in the play area, leading them to reach the limits of the play area. As a result, they had to pay attention to their actions, which was something that broke presence and reminded them of the real world. However, in this question most of the users did not notice any distraction from any method, thus the None answer dominated.

When the users asked about their favorite method, those that selected the Headset-based as their favorite, mentioned it was reasonable, so they were able to learn it easily. On the other hand, in the Feet-based direction source, many users said that they felt comfortable moving freely, that they had the potential to get a lot better, and that it reminds them of walking. Moreover, some of them mentioned that they would like to reuse this method in other applications since they liked it.

6.7 Observation Results

In this subsection are presented some observation results that we gathered from the captured videos of the experiments. As mentioned in the Study section, we recorded the behavior of the users in both the real and the virtual world. We analyzed that video and identified moments that are repeated or were worth mentioning.

Our main observation is that some users maintained a static pose (like a statue) in every method. Specifically, rather than utilizing the current enabled method, they preferred to turn their whole body around and maintain their pose. In this way, by turning the whole body around, some methods operated in the same manner. As a result, with this game style, these users did not notice any major difference between the methods. This behavior was boosted by the fact that many of the required turns that the users had to make were 90 degrees. Therefore, the users had to turn their whole body regardless of the active source of direction, since none of them provides such flexibility.

Another remarkable observation was that some users had a hard time approaching the interaction points. For example, when they had to grab a cube or interact with an input panel. It was observed that these users used to stop a long distance away from these points like they could not measure the distance. As a result, they were unable to reach it. However, the remarkable part is that most of them, either were taking physical steps in the real world or they were stretching their body to reach it. This reaction shows that they tried to avoid virtual movement, and it was observed regardless of the methods. So, we think that is related to the fact that starting and stopping, meaning the phases where velocity changes rapidly, lead to greater motion sickness. Therefore, these users did not feel comfortable using virtual locomotion for moving small distances and preferred to resort to physical movement.

Another fact that was observed and also mentioned multiple times in the interviews was that the Feet-based direction source had the greatest displacement. The users used to turn around a lot, and take unnecessary steps in all directions, ignoring the limited tracked area. This had, as a result, to reach the boundaries of the play area and break presence, and also to request help to replace them in the middle of the play area.

7. DISCUSSION

In this section, some analyzed results are discussed and combined to conclude some findings. It is structured with the summarized results according to our terms of evaluation and our hypotheses, then the limitations that we faced are discussed, and at last, the future work that could expand our research.

As it is mentioned, we evaluated our four direction sources in terms of performance, motion sickness, preference, and presence. According to these axes, we try to find the ideal direction source on CAL.

In terms of **performance**, the results showed that with the Headset method, the users executed the requested tasks faster, achieving the least duration. A significant difference in this was shown in the color game task, which required more interactivity and turns. Then, follow the Hip and the Feet method with similar performances. The users were slower with the Controllers method, meaning that this method made it more difficult for them to complete the tasks fast. This rejects our H2 hypothesis that mentions that the users will be faster with the Controllers method. About the performance of the methods in the zig-zag task, all the methods had almost the same mean duration to complete it. The best accuracy was achieved by the Hip and the Feet methods, having a significant difference from the Headset and Controller methods. The users got out of the path the least times with the Feet method, having many of the users mentioned that they felt confident with this method, by looking at their Feet inside the path. Those results, verify our H1 hypothesis, which says that the Feet-based method will perform the best with regard to accuracy. Moreover, the most duration spent out from the path was with the Headset method, which shows that either they could not easily reset their position fast or they did not notice it soon. The least duration out of the path was with the Hip method. In the corridor task, the users had almost the same mean duration to complete it with all the methods. Moreover, they counted more accurately with the Controllers method, and worse with the Headset. This behavior shows that Headset methods would make it more difficult for users to count the dots correctly. Probably this is because they would not be able to move independently where they look, leading them to unwanted movements. As a result, we believe that the Headset method as a direction source on CAL, reduces visual observation. With the Hip and Feet methods, the results were similar and not bad. Last, in the Color Game task, the methods that the users had the least duration were the Headset and the Feet methods. To sum up, in terms of performance, as the logged data showed by the requested tasks, the Feet and Hip methods appeared as the optimal methods to perform different virtual tasks, since regardless of the task they showed that the users can have a good performance.

In terms of **motion sickness**, the results showed that none of the users, with any of the methods, experienced symptoms to any significant extent. Moreover, the differences between the methods were minimal. So, our H3 hypothesis, which mentions that the Feet-based method will include the least motion sickness, is rejected. Therefore, the direction source on CAL does not affect motion sickness. However, it is worth mentioning that the least motion sickness symptoms appeared with the Headset method and the most with the Hip method. Moreover, the most commonly appearing symptoms were general discomfort, sweating, and dizziness to users.

The **preference** of the users, which was evaluated by their answers in the immersed questionnaires and from the comparative questionnaires, was for the Headset and Feet methods. In immersed questionnaires, the Feet-based method stood out and scored the highest results in all the questions. It was considered to be the most natural with significant differences from the rest, and also the most consistent with also significant differences. This verifies our H4 hypothesis that the Feet-based method will be considered the most natural direction source. Moreover, the Feet base method also scored higher as the best for controlling the movement, the easiest, and the funnest. However, in the post-study questionnaires, where the users were asked comparatively about all the methods, the Headset-based appeared to be selected as the easiest to use method, the one that made the user feel more effective and more natural. However, in this questionnaire, the Feet-based method follows the Headset in the previous categories and was also selected as the favorite of the users. Furthermore, it is worth mentioning that the Controllers method was not preferred at all, scoring as the most difficult to use method, the least effective, the least natural and consistent with a significant difference from the others, and the least favorite. To sum up, in terms of preference, we believe that the Feet-based method stood out along with the Headset and the Controller method was the least preferred.

Presence was evaluated in the post-study questionnaire, in the AS4 question. The Feet-based method led to the displacement of the users, making them reach the borders of the play areas many times. Therefore, this behavior led to the most breaks in the presence of the users' experience. Thus, we can assume that this method requires a lot of space for the play-area to avoid distracting the users' experience. However, many users did not feel that any method distracted them from the VR experience. It is also worthy to mention that the Feet-based method was considered the most natural and most consistent, having significant differences from the rest, at the IQ2 and IQ4. These questions were picked from the Presence Questionnaire (PQ), so we can assume that based on them, the Feet-based method created a strong sense of presence. Therefore, we don't have clear results for this category.

To sum up, in terms of performance, the Hip and Feet methods proved to be ideal for doing different virtual tasks, motion sickness showed that it is not related to the direction source on CAL, and the users showed a preference for the Headset and Feet methods. Last, the Feet method showed that it requires large play-areas to maintain the sense of presence in users. In this way, we are happy to see that the Feet method performed so well in our evaluation, since it was our suggestion regarding the direction source issue.

7.1 Limitations

The main limitation that we had to cope with was that the experiment was conducted during the COVID-19 pandemic, so we had to follow all required precautions to ensure the safety of the participant and conductors. As a result, all the users had to wear a protective mask during the experiment. However, many times masks blurred the lenses of the VR goggles, which need constant and usual cleaning. This issue was annoying for the user and led to multiple breaks in the experiment.

Another limitation was the battery life of the hardware. Specifically, the battery that maintained the VR goggles wireless, was uncharged far faster than the charging phase during the experiment. That created the risk of running out of battery in some cases. Luckily that did not happen.

Last, another limitation that we faced is the experience of the users. The Headset and Controllers as a direction source method are commonly used by VR users. As a result, many users had already experienced these methods, and they were fond of them. Therefore, that was not fair for the rest direction source in terms of the performance. Regardless that the users had time to train with all the methods, many of them mentioned that they would like to utilize them in other VR experiences to explore and learn them more. So, some results may not be objective

7.2 Future Work

In this study, we mainly checked the accuracy of each method in a path where the turns were 90 degrees. This topology pushed some users to maintain a static play style, meaning, the users used to rotate their whole body and did not utilize the capabilities of the used method. An improvement of that would be to evaluate the accuracy in a VE with multiple turns in different degrees. In this way, it will force the users to use more of each method rather than “cheating” by rotating the whole body.

Furthermore, our study could be repeated similarly to explore the effects of different direction sources on the embodiment, by providing a virtual body on the avatars.

Our study examines the effects of different direction sources with CAL. However, in future work, these effects could be examined with different LTs that the moving direction is based mainly on the Headset or Controllers. Such LTs are the most gesture-based, like WIP and arms swinging. Specifically, in WIP the users march to a point, but they move toward where their heads or controllers are pointing. This behavior may feel even more unnatural and weird since it approaches physical walking, but it operates differently. Thus, a Hip-based direction source may feel more familiar. Moreover, different feet-based techniques can be implemented while the user marches on point, which could improve the sense of presence. Therefore, it would have a lot of scientific interest to examine these different sources with another LT.

7.3 Conclusion

This thesis presents the design, analysis, and results of an experiment focused on the effect of different direction sources for CAL in VR. Literature about LTs mainly focuses on ”how to move” the user, and not on the direction of movement. In most cases in CAL, the direction of movement is driven either by the headset or the controllers, i.e. devices that are already tracked by the tracking mechanism of the VR system. However, this approach may not feel so natural to the users, and it may overload the headset and the controllers with navigation functionalities. In this study, we utilize extra tracked devices to unlock different direction sources. One positioned on the user’s hip by placing a tracker in that area, and another positioned on the user’s feet. We evaluate these four direction sources in terms of the user’s performance, preference, motion sickness, and presence. To evaluate, we designed and implemented a VE, and conducted a user study with 24 participants. The users had to fulfill three tasks with each method. Data were collected both quantitatively and qualitatively. The results of our study indicated that the hip and feet methods are the optimal selection in terms of performance for executing different virtual tasks; that motion sickness is not affected by the different direction sources; and that the users preferred the feet and headset methods.

ABBREVIATIONS - ACRONYMS

HMD	Head Mounted Display
VR	Virtual Reality
3D	Three Dimensional
VE	Virtual Environment
DOF	Degrees Of Freedom
LT	Locomotion Technique
ALT	Alternative Locomotion Technique
RW	Real Walking
RDW	Redirect Walking
ROT	Reorientation Technique
WIP	Walking In Place
TP	Teleportation
JS	Joystick

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