NOVA SCHOOL OF SCIENCE & TECHNOLOGY
DEPARTMENT OF COMPUTER SCIENCE

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B.Sc. in Computer Science and Engineering

NON-EUCLIDEAN VIRTUAL REALITY

NATURAL NAVIGATION OF LARGE VIRTUAL INTERIORS THROUGH REDIRECTED WALKING IN SMALL PHYSICAL SPACES

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Acknowledgments are personal text and should be a free expression of the author.

However, without any intention of conditioning the form or content of this text, I would like to add that it usually starts with academic thanks (instructors, etc.); then institutional thanks (Research Center, Department, Faculty, University, FCT / MEC scholarships, etc.) and, finally, the personal ones (friends, family, etc.).

But I insist that there are no fixed rules for this text, and it must, above all, express what the author feels.

"You cannot teach a man anything; you can only help him discover it in himself."

— Galileo, Somewhere in a book or speach
(Astronomer, physicist and engineer)

Abstract

The purpose of this thesis is to improve how Virtual Reality (VR) users can navigate a large virtual room, whilst in a small physical space. The objective is to study and implement overt and subtle navigation redirection techniques, contributing to the research of immersive VR navigation in restricted physical spaces using Non-Euclidean Spaces and Redirected Walking (RDW).

VR applications that grant users the ability to navigate in a very large Virtual Environment (VE) are often limited by the physical space in which they are used in. Thus, solutions for this problem have been proposed through the form of different locomotion techniques. Controllers provide a simple solution to this problem, by allowing users to navigate virtual worlds while standing still, however controller-based approaches have shown to be a less immersive solution for this problem compared to walking. By employing natural physical motion, Redirected Walking (RDW) techniques have shown to be a more immersive solution, yet these often demand a larger tracking space to achieve its full immersive potential.

We intend to provide two alternative redirection techniques, Turn-and-Place and Hyperbolic Rooms, that allow navigation in constricted physical spaces, while prioritizing immersion, through the use of space subdivision for reorientation and hyperbolic spaces, respectively. These techniques may be used in VR applications that prioritize immersion, such as those of entertainment and education, thus the implementations of these techniques will thematically follow those of a virtual museum experience.

The techniques will be evaluated through user studies, to validate their efficacy and usability, as well as a comparison study between them, to identify each of their strong points and limitations.

Keywords: Virtual Reality, Redirected Walking, Non-Euclidean Spaces, Navigation, Human-Computer Interaction

Resumo

O propósito desta dissertação é aprimorar a forma como os utilizadores de Realidade Virtual(RV) podem navegar num ambiente virtual de grandes dimensões, estando confinados a um espaço físico reduzido. O objetivo consiste em estudar e implementar técnicas de locomoção com base em redirecionamento, tanto explícito como subtil, contribuindo assim para a investigação de métodos de navegação imersiva em RV em espaços físicos limitados, recorrendo a Espaços Não Euclidianos e a técnicas de *Redirected Walking*.

Aplicações de RV que permitem aos utilizadores explorar um ambiente virtual de grande escala encontram-se, frequentemente, limitadas pelas dimensões do espaço físico onde são utilizadas. Por esta razão, têm sido propostas soluções para este problema através de diferentes técnicas de locomoção. Comandos oferecem uma solução simples, permitindo que os utilizadores naveguem em ambientes virtuais enquanto permanecem imóveis, contudo, as abordagens baseadas em comandos demonstraram ser menos imersivas quando comparadas com a locomoção por caminhada. Ao empregar movimentos físicos naturais, as técnicas de *Redirected Walking* têm-se revelado uma solução mais imersiva, embora, frequentemente, exijam um espaço de rastreamento mais amplo para atingir o seu pleno potencial imersivo.

Propõe-se a implementação de duas técnicas alternativas de redirecionamento: Turn-and-Place (Virar e Posicionar) e Hyperbolic Rooms (Salas Hiperbólicas), que permitem a navegação em espaços físicos restritos, priorizando imersão, através da subdivisão de espaços para reorientação e da utilização de geometrias hiperbólicas, respetivamente. Estas técnicas poderão ser aplicadas em cenários de RV que privilegiem a imersão, tais como os da área do entretenimento e da educação, pelo que as suas implementações nesta dissertação seguirão uma temática alinhada com uma experiência de um museu virtual.

As técnicas serão avaliadas através de estudos com utilizadores, com o intuito de validar a sua eficácia e usabilidade, assim como de um estudo comparativo entre ambas, de modo a identificar os pontos fortes e as limitações de cada uma.

Palavras-chave: Realidade Virtual, Redirected Walking, Espaços Não Euclidianos, Navegação, Interação Pessoa-Máquina

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Acronyms

6DOF 6 Degrees of Freedom *(pp. 7, 8, 43)*

AR Augmented Reality *(pp. 8, 9)*

FOV Field of View *(pp. 8, 17, 24)*

HCI Human-Computer Interaction *(p. 7)*
HMD Head-Mounted Display *(pp. 5, 7–9, 14, 15, 17, 32, 34, 35, 42, 43, 52, 53)*

ODT Omnidirectional Treadmill *(pp. 8, 21)*

PC Personal Computer *(p. 8)*

RDW Redirected Walking *(pp. v, 1–3, 5, 15, 17, 19–21, 23–26, 30, 31)*

SDK Software Development Kit *(p. 9)*

UX User Experience *(pp. 1, 3, 5, 32, 60, 61)*

VE Virtual Environment *(pp. v, xi, 1–5, 7–21, 23–26, 30–36, 42, 52, 53, 60, 61)*
VR Virtual Reality *(pp. v, x, 1–5, 7–13, 15, 17, 19–21, 23–26, 29–36, 42, 43, 52, 55, 59, 60)*

1 Introduction

Virtual Reality (VR) is an immersive technology, with the capacity to transport users into interactive computer-generated 3D Virtual Environment (VE). Unrestricted by the laws that bind the real world, VEs can bend or dismiss these rules to create virtual spaces that are impossible to experience otherwise. As such, VEs can be larger than the physical environment VR users have available while navigating these virtual worlds.

To resolve this real-world limitation, different locomotion techniques have been developed. The most common techniques rely on the use of artificial means for locomotion, such as controllers, yet these have shown to be a less immersive solution than naturally walking in a physical environment. Therefore, VR applications that prioritize immersion often rely on the use of motion-based techniques such as Redirected Walking (RDW), to allow users to physically walk in their restricted space safely, without reaching the ends of their tracking space.

1.1 Motivation

The implementation and exploration of immersive VEs has evolved with the development of VR and its wide range of locomotion techniques. These techniques influence dimensions of User Experience (UX), such as efficiency, usability, immersion, comfort, and accessibility, and are, therefore, used in different contexts and situations [6].

One of the main challenges of VR locomotion is the physical limitations users face when navigating a VE. The most common techniques rely on the use of controllers for locomotion, such as teleportation and joystick-based movement [13], due to the fact that controllers do not warrant users' movement and there is a familiarity with them from the video-game scene. Although artificial techniques have shown to be an efficient and appropriate method of locomotion in VR, the lack of a walking motion makes these techniques less suitable for use-cases in which immersion is prioritized, as a natural walking motion provides higher feelings of presence by mirroring how humans walk in the real world [39].

Locomotion techniques that rely on users to walk in their physical environment have shown their benefits in immersion and presence. Motion-based techniques include the use of gestures that emulate walking, such as Walking-in-Place or Arm-Swinging, or the use of artificial devices that counter-act users' movements while walking, keeping them in place, such as Treadmills. These techniques have shown to be a preferable solution for higher feelings of immersion than controllers [39].

RDW refers to a group of techniques for locomotion in VR that allow users to naturally walk through their VE, by keeping users inside their available space through a variety of different redirection methods [38]. Although most commonly associated with methods such as rotational gains, that play with the imperceptibility of human senses to slowly direct users to their available space, RDW techniques can employ redirection with more overt strategies for safety-risking cases or others in which imperceptibility is kept by discreetly changing the VE in real-time, while the user is navigating it. Despite being a promising solution that enables walking in restricted spaces, it usually needs to be employed in use-cases in which users' tracking spaces are approximately 5 x 5 meters, where gains remain imperceptible to users [23, 49]. However, the average available physical area for VR users is approximately 2.4 x 2.2 meters [3, 31].

Given the possibilities of shaping rules of reality in VR, a form of implementing RDW is through the use o Non-Euclidean Spaces. By employing non-Euclidean properties it is possible to map larger VEs into a limited tracking space, by using overlapping-architectures that break the laws of Euclidean Geometry [52, 55] or by mapping Euclidean coordinates into a hyperbolic plane [40, 45].

Portals are commonly used to connect multiple sections of a self-overlapping architectural layout, typically functioning as doorways that allow users to seamlessly travel between locations within a VE through bidirectionally paired connections [17, 33, 31]. The seamless transition from one section to another is achieved through a stereoscopically rendered plane, enabling users to preview the connected space as if they were already positioned at the destination, with the appropriate transformations of location and rotation relative to the portal [33, 22].

However, portals as a means of locomotion have shown its limitations in previous studies [42, 43]. To prevent users from leaving the limits of their physical tracking space, portals must be placed within a certain distance from the boundaries of the corresponding VE. This has an impact on the portal's preview, as the closer the portal is to said limits, the less space will be observable through the preview, since the rendering of the portal view is dependent on the position of the portal. Additionally, positioning portals within a certain distance from these limits hinders the amount of available space in an interior VE, as well as its naturalness, due to the unreal-like appearance of a floating door frame away from a wall.

With this context in mind, the goal of this dissertation is to contribute to the research of RDW in small physical spaces, through the design, implementation and study of portal alternatives, aiming to counter-act the previously mentioned limitations. This work pretends to enhance navigation experiences in VR, making virtual experiences more accessible, particularly in home settings, where users typically have no more than 2.4 x 2.2 meters of space to walk.

1.2 Objectives and Research Questions

The main objective of this dissertation is to contribute to the research of RDW in limited physical spaces through the design, implementation and study of portal variants for RDW in small tracking spaces. To complete this main objective, smaller particular goals have been identified for conducting this research:

- **Explore different VR locomotion techniques and their effects on UX**: Investigate existing locomotion methods in virtual reality, analyzing their impact on usability, immersion, and overall user experience.

- **Design and Implement alternative portal techniques**: Conceive and accomplish each of the techniques, addressing each of the most common portal limitations found in previous studies.

- **Conduct user studies to evaluate the techniques**: Conduct empirical studies with participants in order to assess the usability, effectiveness, and overall user experience of the proposed portal techniques.

In order to better structure this research, the following three research questions are proposed:

- **Q1 - What are the effects of a dynamic preview in regard to users' sense of space?** - One of the identified limitations of using portals as a VR locomotion technique in small physical spaces is a lack of a proper preview. This research question explores the impact on users' perception of space when using alternative VR portal techniques that counteract this limitation by dynamically changing their previews.

- **Q2 - What elements of UX do users prioritize when interacting with these navigation techniques?** - This question investigates which aspects of the user experience participants value most during navigation, such as spatial orientation, ease of use, naturalness, or comfort, providing insights into user priorities across different navigation techniques.

- **Q3 - What are the strong points for each of these techniques, in regard to VE navigation?** - This question seeks to identify the comparative advantages of each portal technique, highlighting the contexts in which a given approach offers superior usability, efficiency, or user satisfaction within virtual environments.

1.3 Solution Overview

Our solution relied on the implementation of three distinct portal variants that address the limitations of VR navigation using portals. These variants were compared with an implementation of traditional portals through a user study, taking a museum tour as a use-case, where participants explored a museum VE using each of the developed portal variants, bound by a physical space of 2.5m x 2.5m.

A more detailed description of the design choices and implementation of each of the portal variants is present throughout the document, however, a general definition of each of the techniques are as follows:

1. **Traditional Portals (Baseline)** - A simple framed portal with a stereoscopically rendered preview, always placed within a minimum walkable distance from the limits of the VE. To use this portal a user must solely walk through the frame.

2. **Movable Portals** - A framed portal initially placed at the wall that users can move by grabbing the portal through a handle-like affordance present in the frame. When grabbed users may choose the placement of the portal inside a valid area by letting go of the portal. When the portal is against the wall the preview is reversed so that the preview may be continuous to the next room. Placing the portal makes it rotate, reversing the preview. To use this portal the user must grab it, place it and then walk through it.

3. **Interactive Doors** - A door-shaped portal, complete with a door-frame and handle, placed against the wall. The door changes its appearance according to user's proximity: opaque when near, transparent when distant. Given this, the portal is visible from a distance, displaying a continuous preview that becomes less visible when users approach it. The door can be opened when fully opaque by grabbing the handle in the door-frame, with the portal following the door-frame with the motion. After opened the user may teleport to their destination by walking through the opened door.

4. **Revolving Doors** - A compartment in the VE with a revolving door, that similarly to Interactive Doors, changes its opacity according to user distance. From afar the door is transparent, making the portal's continuous preview visible, but when approached it becomes opaque and interactable. To use the portal the user must push the door and perform a 180-degree turn.

A user study was conducted using these portal variants, comparing various usability factors between the baseline of traditional portals and our variants, as well as between each other. This study aimed to gather data on each of the portal's impact on user preference, usability, spatial understanding, presence and comfort.

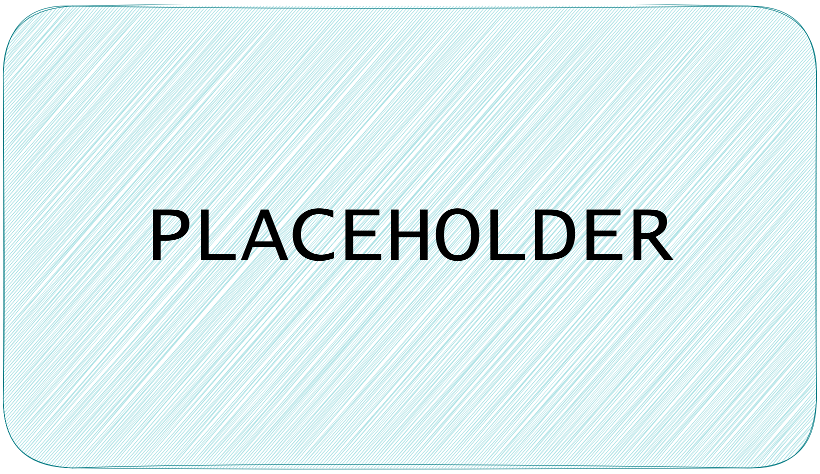

Figure 1.1: The four portal techniques studied in this thesis: Traditional Portals, Movable Portals, Interactive Doors and Revolving Doors.

1.4 Contributions

This work contributed to further research the use of Redirected Walking (RDW) techniques in small physical spaces, through the design, implementation and study of new variant portal techniques that address identified limitations of common portal techniques used in VR applications and research. The main contributions of this thesis are:

- The design and implementation of three VR locomotion techniques using portals;
- The study of the portal variants in comparison with portals commonly seen in VR applications and research;
- Insights on the impact these techniques have on UX;
- Insights on design guidelines for VR locomotion;

The study done for this thesis has additionally resulted in the submission of a full paper to ICAT-EVGE, detailing the developed portals and presenting and discussing the results of the study.

1.5 Document Structure

change according to the final document

Following this section, the main goal of the Related Work chapter is to explore the literature on this topic. The chapter starts by presenting Head-Mounted Displays (HMDs) and devices used in VR, as well as how Navigation occurs on VEs, followed by an exploration of several different common types of VR Locomotion techniques, with one of them being an extensive exploration of RDW techniques. Lastly, this chapter finishes by addressing two types of Non-Euclidean Spaces in VR: Impossible Spaces and Hyperbolic Spaces.

The **??** chapter describes the proposed solutions in detail, and addresses the user studies to be conducted. This chapter also includes a section on the preliminary work accomplished to the present date and finishes by addressing the planned work to be done during the dissertation.

2

Related Work

With the objective of understanding the current state of the art in the field of Virtual Reality (VR) navigation and locomotion, this chapter presents several topics, techniques and studies that are relevant to this field.

2.1 Virtual Reality

VR has been given various definitions [34], but these tend to converge on the same few essential ideas: VR is a real-time, interactive and immersive experience in a simulated 3D World (commonly referred as Virtual Environments (VEs)), made possible through the use of different technologies, as Head-Mounted Displays (HMDs) and several input/tracking devices that have been in active development and research as of late [7].

It is through the understanding and correct application of these technologies and research that a VR application can realize its full immersive potential [28]. Recognizing that this is one of the key points in VR development [48], this section is dedicated to the exploration of said literature and technologies.

2.1.1 Head-Mounted Displays and Devices

The start in development of consumer accessible HMDs in 2012 can be considered the initial spark of the denominated second-wave of VR development, greatly contributing to research in the field of Human-Computer Interaction (HCI) [2]. This wave of development is still underway and with it new devices are being introduced into the market [28].

HMDs consist of two screens mounted in a glasses-like device that are fixed relative to the eye position of the wearer, and portray the VE by obtaining their head orientation and position of the wearer from a tracking system [47]. Tracking Systems are, therefore, technologies that permit the correct tracking of the position and head movements of the user according to the 6 Degrees of Freedom (6DOF) [2] - **Surge**, **Sway** and **Heave** - translational movements in the x, y and z axis, respectively - and **Pitch**, **Yaw** and **Roll** - rotational movements in the x, y and z axis, respectively.

According to Anthes et al. [2], HMDs can also be divided into two different categories:

- Wired HMDs - These devices need to be connected to a powerful Personal Computer (PC) in order to function. The differences between the devices of this type range from the screen's resolution, Field of View (FOV), weight, as well as additional features such as cameras that permit Augmented Reality (AR) capabilities and eye tracking systems to record the users gaze. They are typically empowered by an external 6DOF tracking system provided by the manufacturer of the HMD, such as the *Base Stations* provided alongside the *Valve Index*[1] HMD.
- Mobile HMDs - These range from HMDs with a computing system within the headset to frames and cases for smartphones with additional lenses, but all share the property of not being dependent on an external PC. Wired HMDs tend to have better specifications, but later developments of HMDs, such as the Oculus Quest 3[2] have changed this perspective, by providing high resolution(2064x2208) display specifications and pairing it with high resolution cameras and sensors, such as gyroscopes, accelerometers and magnetometers for tracking systems that allow wireless 6DOF and Hand Tracking (Figure 2.1).

Input devices also have their importance in user interactions with VEs [28], with these taking multiple forms. Controllers are the most common within the VR space [2, 7], demonstrating similarities with the familiar video-game controllers with the inclusions of buttons for discrete input, and joysticks and triggers for continuous input. VR controllers distinguish themselves from the video-game ones by including 6DOF tracking capabilities and by integrating gesture-recognizing sensors.

Other input devices range from Gesture Tracking devices, with data gloves as an example, to navigation devices, such as Omnidirectional Treadmills (ODTs) and Zero-Friction Surfaces [2, 39].

[1] Valve Index Information Page - https://www.valvesoftware.com/en/index, Last Access - Feb 2025
[2] Oculus Quest 3 Information Page - https://www.meta.com/quest/quest-3/, Last Access - Feb 2025

Figure 2.1: The Oculus Quest 3 and its Controllers. The headset's frontal cameras and IMU(Inertial Measurement Unit) allow a wireless 6DOF and gesture tracking system.

2.1.2 Development of VR Applications and Environments

Tools and technologies have emerged alongside the "second-wave" of VR development [2], making VR application development more accessible. Popular 3-D game engines, such as *Unity*[3] and *Unreal Engine*[4], are examples of tools that support VR development. These engines help developers streamline the process of creating VEs and the interactions that occur within them, through the use of diverse plugins and libraries for XR development.

OpenXR[5] by *Khronos Group* is an open, royalty-free standard for VR and AR applications. This standard defines a unified interface for developers to use when developing VR/AR applications, providing cross-platform compatibility between various HMDs, so that low-level programming for these platforms is more accessible, since developers do not need to program the application according to each of the Software Development Kits (SDKs) from each platform.

Due to the availability of these tools, the scientific community has been using them to create VR applications and environments [2]. This research is included in this group, as the *Unity* game engine will be used along with *OpenXR* plugins to develop the applications of our proposed solution.

2.1.3 Navigation of Virtual Environments

Due to the immersive yet controlled nature of VR, one of its effective applications involves the study of human navigation behavior [15]. This research belongs with those studies, thus it is relevant to have an overview on this matter, as well as understanding its nomenclature, which is the purpose of this section.

Navigation can be broken down into *Motion* - its physical element - and *Wayfinding* - its cognitive element [14]. The model constructed by Jul and Furnas [24], as seen on Figure 2.2 is considered a relatively complete representation of how Navigation takes place, since it takes both these elements into consideration.

Wayfinding involves no movement of any kind, and its primary purpose is to construct and keep a *cognitive map* [27], also referred to as *mental maps*, which, as the name suggests, is a mental representation of an environment. Although it may be instinctive to call it a "picture in our heads", studies have come to suggest that these cognitive representations are not strictly visual but also symbolic [14, 57]. The quality of a *cognitive map* is then dependent on the method in which the spatial knowledge is acquired, as results of accurate spatial orientation differs from understanding a map to navigating non-immersive VEs (such as those of video-games on a screen) and immersive VEs [14, 47]. Even then these results can be inconclusive, as the properties of VEs affect the intake of spatial knowledge.

Motion, also referred as *Locomotion* or *Travel*, is the motor element of Navigation that allows the physical translation from one location to another [47]. The properties of motion

[3]Unity Documentation - https://docs.unity3d.com/Manual/index.html, Last Access - Feb 2025
[4]Unreal Engine Documentation - https://docs.unrealengine.com/, Last Access - Feb 2025
[5]OpenXR Main Page - https://www.khronos.org/openxr/, Last Access - Feb 2025

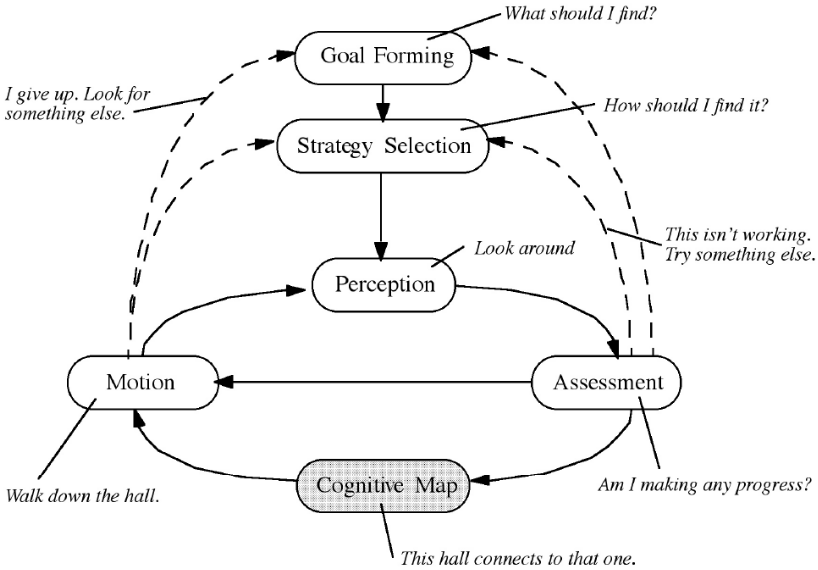

Figure 2.2: Model by Jul and Furnas that demonstrates the motor and cognitive elements of Navigation [14].

have implications on the intake of spatial knowledge, as for instance, if locomotion in a VE is discrete instead of continuous, users tend to have more difficulty in fully comprehending their surroundings [27]. This and other properties of locomotion are then going to be discussed in the following sections of VR Locomotion Techniques and Non-Euclidean Spaces in VR.

2.2 VR Locomotion Techniques

Locomotion (also denoted as "active travel" or just "travel" [27]) - the act of moving from one location to another - is often considered one of the key aspects of VR interaction [38], as it permits navigation in VEs [6].

Throughout the advancements in VR research and technology, multiple locomotion techniques have been developed, all with different characteristics, addressing different needs and use cases [7]. It is due to the diversity of these techniques that various taxonomies and classifications have been proposed, throughout the years of VR development [7]. The structure of this subsection is based on the typology of VR Locomotion Techniques proposed by Boletsis et al. [7] as it encompasses most techniques according to the characteristics discussed in this section.

According to Boletsis et al. [7] locomotion techniques are distinguished by the type of interaction they require, the type of motion it produces and the type of VE it is designed for, as seen in Figure 2.3.

Regarding the interaction type, a locomotion technique can be "physical" - the input is based on physical movement - or "artificial" - utilizes input devices for direct VR motion

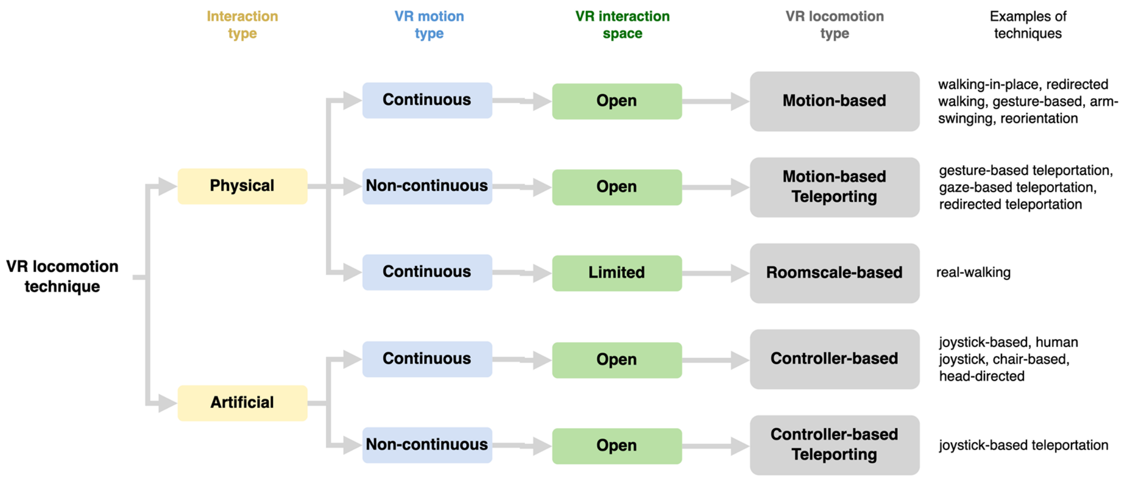

Figure 2.3: Typology of VR locomotion techniques by Boletsis et al. [7]

and navigation. VR motion types may be "continuous" - the transitions between positions is smooth and non-interrupting - or "non-continuous" - the transitions between positions are abrupt or instantaneous. Finally, the VR interaction space may be "open" - the VE is larger than the tracking space being used - or "limited" - the physical environment constraints the size of the VE.

Different sets of these characteristics define the different types of locomotion techniques that are to be discussed in the following sections. It is also important to note that these techniques may be used in combination with each other, i.e., a technique integrating two or more other techniques [7].

2.2.1 Controller-Based

Controller-Based locomotion techniques are used in an open VR interaction space, with continuous motion and require an artificial means of input, such as a controller or other similar input devices [5]. Joystick-based locomotion is not only the most prevalent of this type of techniques, it is also one of the most used techniques in research [7].

Joystick-Based locomotion can be described in the following manner: given a user in a VE from a VR application, the way that they navigate in said VE is dependent on a joystick controller. The joystick rests in a neutral position until the user applies force, changing its value in a certain axis, normally from -1 to 1 (see Figure 2.4). The values registered on the horizontal and vertical axis will make the user continuously translate from one position to the next in the direction related to the user's gaze direction, i.e., if the user is looking in a certain direction and applies vertical of 1 they will move in the yaw direction of their gaze at full speed [13]. The artificial means of creating input for movement makes joystick locomotion considered not physically demanding and a high ease-of-use technique, especially noticed in users who have prior experience with similar controllers [37]. This locomotion type also registers moderate-to-high levels of immersion

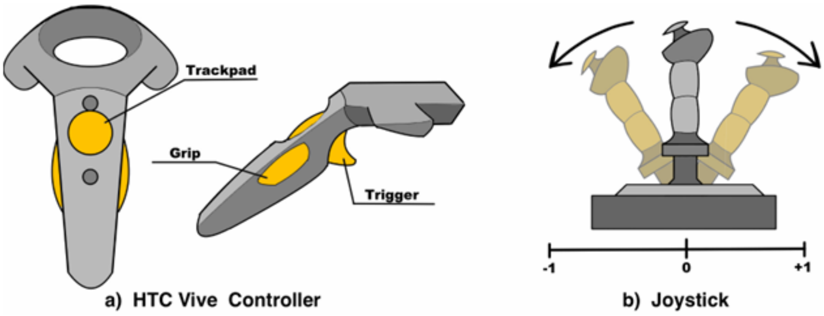

Figure 2.4: Diagram of Vive Controller and Joystick [13]

when used, mostly due to the motion's uninterruptible nature [6].

Though intuitive and not physically demanding, joystick locomotion has a caveat that pertains to the discomfort users might feel during motion. This locomotion type can create motion sickness, due to the conflicting movement cues from user's proprioception, their vestibular sense and from their vision, as the user is physically stationary whilst they move in the VE [27]. This is especially felt by inexperienced VR users [37].

2.2.2 Teleportation

Teleporting differs from Controller-Based locomotion techniques in that it is non-continuous, as, instead of moving continuously, users are teleported from one location to the next in an interrupted manner during their navigation [5], and, similarly to Controller-Based-Based locomotion, it is one of the most used locomotion techniques [7].

When teleporting, a user dictates where they want to teleport to, usually by holding down some input button on a controller and pointing to the pertained destination with said controller, releasing said input when the destination has been chosen. On release the user moves to the selected destination instantaneously (see Figure 2.5) [13, 37].

The discontinuity of this locomotion method creates strengths and weaknesses. On the positive side, the discrete jumps prevent feelings of cybersickness by not having a conflicting continuous motion occurring while the user is stationary [6, 37], and is generally

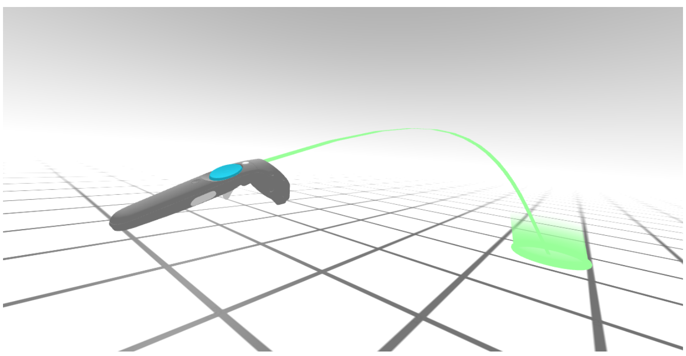

Figure 2.5: Graphical Representation of Teleporting[6]

more efficient at covering long distances [13]. On the other hand the jumps can create some disorientation and loss of immersion, as after teleporting the user takes more time to fully comprehend their surroundings [27], exerting more cognitive effort and in turn breaking the illusion of the VE.

To mitigate this lack of immersion, studies tried to provide less artificial manners of performing teleportation. However, even with similar or slightly better results in regard to immersion, users still preferred using controllers rather than the purposed controller-free [8], and even hands-free teleportation techniques [41].

Even so, in various comparison studies, teleportation has been identified as a preferred locomotion method over other frequently used alternatives, mostly due to the lack of motion sickness and high ease-of-use [6, 27].

2.2.3 Omnidirectional Treadmills

As a type of locomotion techniques that require physical interaction for continuous motion in open VR interaction spaces, Motion-Based techniques are rooted on physical movement for navigation in a VE [5], which poses the question: How can a user physically navigate a VE larger than their physical environment without reaching the limits of their available space?

According to Nilsson et al. [39], it is possible to identify yet another three subtypes of Motion-Based locomotion techniques, all of which try to solve this problem, with these being Repositioning Systems, Proxy Gestures and Redirected Walking.

Repositioning Systems refer to input devices that try to counter-act forward motion when users walk, essentially keeping them in place, ranging from more devices with a more "active" approach to the repositioning, such as treadmills to more "passive" options, such as friction-free platforms Figure 2.6.

One of the most common Repositioning Systems are Omnidirectional Treadmills - devices that sense the direction of steps whilst a user is walking in a 360 degree space, maintaining the user at the center of their available space, translating the users steps as

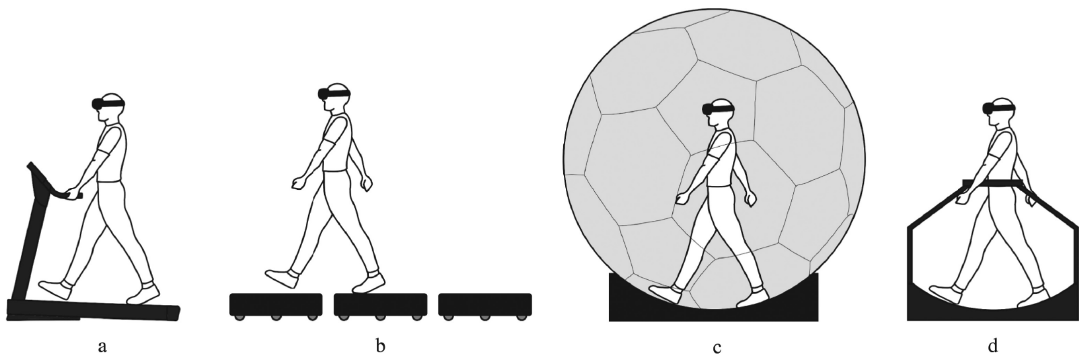

Figure 2.6: Four examples of re-positional systems: (a) Traditional Linear Treadmill, (b) motorized floor tiles, (c) a human-sized hamster ball, and (d) a friction-free platform. [39]

movement in the VE. User studies seem to indicate that the motion caused, although not reaching quite exactly the feeling of real walking (with some users indicating a feeling more similar to running or skating rather than walking), this locomotion method evokes high levels of presence, similar to natural walking locomotion methods [54].

However, despite taking an almost accurate walking motion as input, offering high levels of immersion and providing a promising solution for the physical limitations of walking in a constricted space, these devices are often expensive and tend to be difficult to operate [11]. In addition, performing quick turns or side-steps may cause users to lose balance [39] and more natural walking techniques such as the latter discussed Redirected Walking are preferred by users [54].

2.2.4 Walking-In-Place and Arm-Swinging

Proxy Gestures techniques, contrarily to Repositioning Systems, such as the Omnidirectional Treadmills, offer inexpensive and easy-to-learn solutions to the problem caused by physical constraints during Motion-Based locomotion techniques [39]. Locomotion in these techniques is based on gestures that emulate walking motions, keeping users moving their limbs, but stationary at the same time.

Walking-In-Place is the most common of these techniques [6, 39]. To emulate walking, users perform a gesture comparable to "marching on the spot" in order to move in the direction they are facing, sometimes relying on sensors for detecting leg movements [11], yet the detection can recur solely to HMDs [29] (Figure 2.7).

Although it might sound counter-intuitive for simulating physical walking, Arm-Swinging is a technique that switches the motion performed by users from the lower body to the upper body. In this technique users swing their arms back and forth interchangeably, to move in the direction they are facing. The objective is to perform a gesture comparable to how humans naturally swing their arms when they walk, with arm movements being

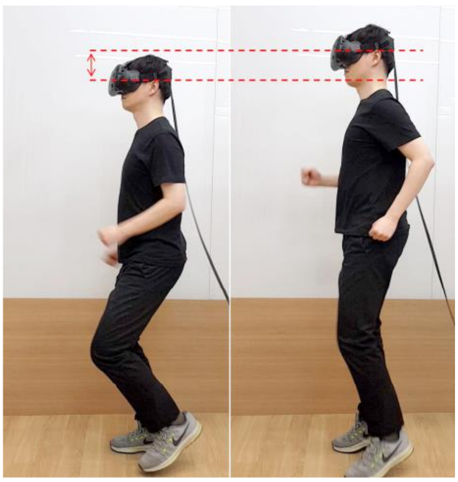

Figure 2.7: A visualization of how Walk-In-Place may be detected by an HMD, through the variance of its position. [29]

detected either by armband-like sensors [11], or just by controllers that users hold in their hands [13].

The fact that both these techniques have the capability to only rely on HMDs and their associated Controllers makes them more accessible, easier to use and thus a more prevalent technique for common users [39]. Additionally, the motion-based input provides a more appropriate proprioceptive feedback similar to real walking than Controller-Based and Teleportation techniques and hence usually grade higher in immersion ratings [6].

Despite this, these techniques present some caveats. Walking-In-Place can be physically demanding and potentially induces motion sickness after prolonged use [6, 11], making it not the best solution for use-cases in which users have to navigate an extensive VE. Arm-Swinging, although not in the same magnitude, is also limited by this weak point [13], but it is additionally limited by the fact that users cannot use their arms for interaction while moving [39].

2.2.5 Redirected Walking

Motion during navigation in VR is an added value to immersion. The previously mentioned techniques - Omnidirectional Treadmills, Walking-In-Place and Arm-Swinging - proved this, since they are regarded as high immersion techniques compared to techniques with artificial means of input (Controller-Based and Teleportation), due to their reliance on gestures that simulate walking [37]. Additionally, Motion-Based techniques also tend to score higher in spatial orientation/awareness, compared to artificial means [11, 13]. Even so, users tend to prefer using Redirected Walking (RDW) over the other motion-based techniques [27, 54].

RDW is not a particular technique, but rather an umbrella term for all techniques that allow users to physically walk in a VE by controlling their path in ways that keep them from reaching the edges of their available physical space [39]. Despite the multitude of possible implementations, RDW aims to follow 4 criteria: **Imperceptibility** - users should be as less aware as possible of the redirection taking place - **Safety** - users should feel as safe as possible from reaching the boundaries of their available physical space - **Generality** - the correct functionality of the technique should be as independent as possible from the physical environments in which they might be used - and **Absence of Unwanted Side Effects** - the technique should aim to be devoid of side effects as those of cybersickness and disorientation [38].

Literature on this topic has recognized two common types of redirection strategies adopted by these techniques [38, 39]:

- **Perspective Manipulation** - RDW techniques that steer users away from the edges of their tracking space by manipulating the mapping between the real and virtual movements performed by users. Manipulation is accomplished by applying repositioning and orientational transformations, such as gains to the users translational and rotational movements i.e. if a gain of 2.0 is applied to the user's forward translation, then they will travel twice as fast in that forward motion in the VE

- **Environment Manipulation** - These techniques rely on the layout and characteristics of theVE in order to accomplish redirection. This is done by either building a VE with a pretended path or by changing the VE's properties whilst the user is navigating it, in order to change the routes taken by users, with the purpose of keeping them away from the limits of their available space.

2.2.6 Overt and Subtle Redirection

To further categorize these techniques, Suma et al. [50] purpose a taxonomy of techniques (observable in Figure 2.8) according to whether these are **Repositioning Techniques** - techniques that compress the VE by manipulating the correspondence between points in the real and virtual environments - and **Reorientation Techniques** - techniques that attempt to rotate the facing direction of users away from the edges of their tracking space. These techniques can then be **Overt** - easily noticed by users - or **Subtle** - changes are hidden from users - and either **Continuous** - the changes are slowly applied - or **Discrete** - changes are immediate.

Subtle Continuous Repositioning and **Reorientation** techniques are associated with the use of Translational and Rotational Gains, respectively, and these could be considered the most prevalent techniques of the mentioned Perspective Manipulation strategy for redirection [39]. These gains compress the VE by deliberately altering the mapping between movements in the physical and virtual spaces (Figure 2.10). Translation Gains scale the steps users take, whilst Curvature Gains are a continuous small rotations applied

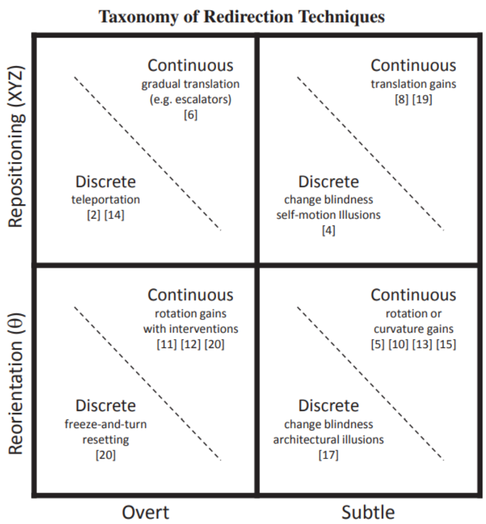

Figure 2.8: Taxonomy of redirection techniques for supporting natural walking through immersive VEs. The vertical axis distinguishes how the technique is applied in the environment. The horizontal axis provides a ranking in terms of notability to the user. The division in cells represents distinct implementation strategies for each type of technique. [50]

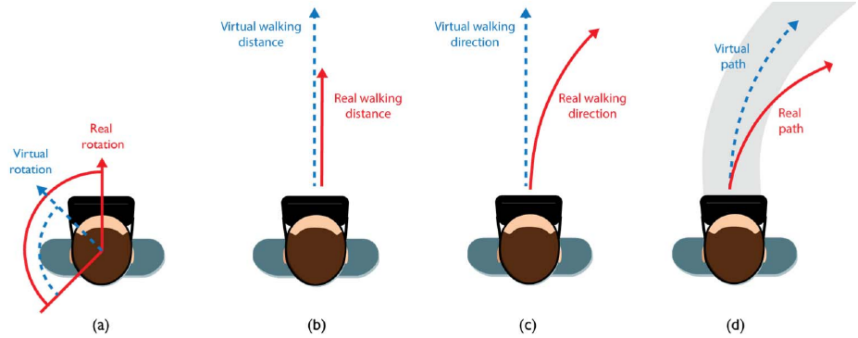

Figure 2.9: Illustration of four types of gains used to manipulate the mapping between the real and virtual movements: (a) rotation gains (user stationary), (b) translation gains (user moving forward), (c) curvature gains (user moving forward), and (d) bending gains (user moving on a curve). [38]

while the user is walking forwards, creating the possibility for users to walk infinitely along a virtual path while walking in circles in their tracking space. Bending Gains are another type of gain that works similarly to Curvature Gains, but these are used in already curved virtual paths. Both Curvature and Bending Gains require either *a priori* knowledge or a good prediction method of the path users take in the VE [38].

Most of the techniques in this taxonomy are associated with a Perspective Manipulation strategy. However, **Subtle Discrete Reorientation** techniques do directly alter the VE making them accurately follow the Environment Manipulation strategy. Change blindness redirection [51] serves as an example of how a technique with this characteristic might be used, as it discreetly makes changes to the environment outside users' FOV, leading them to take different paths without breaking immersion.

With the given nomenclature, **Subtle Discrete Repositioning** might seem counter-intuitive, for how can a VR application make discrete jumps in positions users take without their awareness? Bruder et al. [9] purposed a solution by creating visual optic flow effects, reminiscent of filters or tunnel vision, to mask the discrete jumps in the users position. User studies performed with the implementation of this technique revealed that users were not able to discern the difference between real and virtual movements while influenced by the technique, allowing the redirection to be more imperceptible.

As mentioned, RDW techniques should aim to be as unnoticeable as possible [38], but overt techniques prove valuable in limiting conditions to assert that the technique is safe for use. **Overt Discrete Reorientation** techniques are associated with techniques used to redirect users to the available space when they are near of its limits. Freeze-and-turn is an exemplary "failsafe" emergency technique [58]. When a user is nearing the edge of their tracking space, the display on the users' HMDs freezes and prompts them that a reset is required. Once the user has completed a 180-degree turn, the display resumes. Even if the redirection is easily noticeable, Safety can be prioritized over Imperceptibility for extreme cases such as these.

Overt Continuous Reorientation techniques are then comparable to the previously

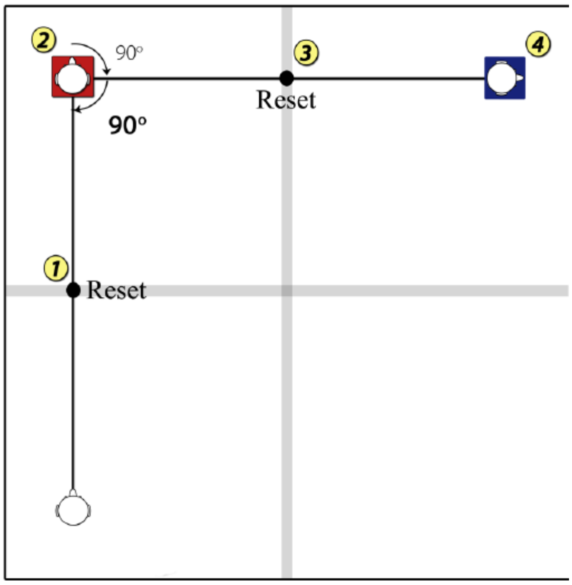

Figure 2.10: Illustration of one of the case studies by Williams et al. [58] when testing the Freeze-and-Turn technique. In a subdivided virtual space, in this case 4 times larger than the available tracking space, whenever a user finds themselves at the limit of the tracking space, they are forced to "reset", by doing a 180º turn while the VE is frozen. The resulting condition is that users keep walking in the direction they were heading in the VE but return to their available space in their tracking space.

mentioned type of technique. The difference lies in the fact that when the system is resetting, the display does not freeze, as when the user is prompted to turn 180 degrees, their movements are being translated as a full 360-degree turn in the VE, allowing them to proceed their virtual path without reaching the edges of their tracking space [58].

Overt Discrete Repositioning relies simply on teleporting the user from one position to the next, which may be disorienting if users are not given enough context and are not expecting the instantaneous change in space. This is mitigated through the use of portals, making the transition more deliberate and potentially a more immersive experience [50]. This serves as an example that overt techniques do not necessarily severely reduce feelings of presence in a VE, if there is a context that justifies the overtness.

Overt Continuous Repositioning techniques simply translate the virtual environment about the user's position continuously, in order to achieve repositioning. This then allows the user to walk on areas in the virtual environment that were not previously accessible within the confines of the physical workspace. To minimize the jarring sensations these techniques may feel, they can be coupled with the use of known metaphors associated with motion such as escalators, elevators and vehicles [50].

It is important to note that techniques may incorporate more than one of the mentioned strategies and types of techniques. The work by Rebelo et al. [42] is an example of this, as the developed techniques rely on the use of portals, alterations in structure of the VE and translation gains, in order to permit the navigation of an extensive VE in a room-scale physical space.

It is also relevant to note that RDW techniques present caveats. These techniques typically need larger physical environments in order to be imperceptible [27], since smaller tracking spaces imply the need for higher value gains and gains need to stay below detection thresholds to remain imperceptible, and thus more immersive [19]. Minimum room sizes and the mentioned gain thresholds are dependent on the techniques being used and remains a challenge for RDW research. [11, 38].

Techniques similar to Telewalk [46] directly address this limitation, as this technique aims to be a locomotion approach that permits navigation in VR in a more natural way to increase presence and immersion, in spaces as small as 3x3 meters. It relies on using intentionally overt Rotational and Translational Gains, with the addition of head-based direction control and visual indicators to help redirect users into an optimal path, as seen in Figure 2.11. The user study conducted by Rietzler et al. [46] compared Telewalk with Teleportation, since, as mentioned previously, the latter is also highly optimal for use-cases in which the tracking space is reduced. Telewalk did result in stronger feelings of presence and immersion and was seen as more natural than Teleportation, mostly accomplishing its purpose, yet users were evenly divided in terms of preference between the two techniques. This was mostly due to an unwanted side effect created by the overtness of the technique, which leads to the next limitation of RDW.

RDW techniques that create a large mismatch between real and perceived motion by using high translational gains can cause VR sickness [18], as well as an increased cognitive load, particularly when overt redirection techniques are applied [38]. The effects vary depending on user characteristics, hardware, and gain configurations, thus an exact relationship between VR sickness and RDW remains unclear and a challenge in VR research [18, 19].

This is one of the challenges to be tackled in this research. After exploring the literature of Locomotion techniques, it is safe to say that RDW techniques provide better levels of immersion and presence in the navigation of a VE. It is, however, limited by the mentioned weak points, but, due to the diverse possibilities of implementations this type

Figure 2.11: Telewalk: The combination of perceivable curvature and translation gains along with a head based camera control allows compressing any virtual space to a predefined real world radius (in this case 1.5m). (Left) illustration of walking paths and (right) plots of the virtual and real path walked in its study application. [46]

of locomotion techniques allows, alternatives that mitigate the problems created by these limitations can still be explored and refined. Thus, the accomplishing of this research's objectives involve the use of the mentioned strategies and techniques of RDW.

2.2.7 Comparing Techniques

Having an overview of the literature on VR locomotion techniques allows for a clearer comprehension of the problem at hand. The objective of this section is to review the mentioned techniques and compare them, connecting their advantageous and disadvantageous characteristics (Table 2.1) to the best use-cases these techniques are optimal for, in search of conclusions that are valuable for addressing this problem.

Table 2.1: Summary of the explored Locomotion Techniques

Technique	**Advantages**	**Disadvantages**
Joystick-Based	Intuitive; Easy to use; Moderate Immersion	Can cause motion sickness due to conflicting sensory cues
Teleportation	Prevents motion sickness; Efficient for covering long distances	Reduces immersion; Increases disorientation; Disrupts spatial awareness
Omnidirectional Treadmills	High immersion; Realistic motion simulation	Expensive; Complex setup; Safety issues
Walking-In-Place	Affordable; Immersive; Minimal hardware requirements	Physically demanding; Less natural than walking; Potential for motion sickness with prolonged use
Arm-Swinging	Accessible; Immersive; Minimal hardware requirements	Limits hand use for interactions; Less natural than leg movements
Redirected Walking (RDW)	Highly immersive; Supports natural walking	Most techniques require larger physical spaces; High gain values can cause VR sickness

After revising the studies made on this matter, it is possible to conclude that Continuity provide higher levels of presence in the VE, since discreet jumps between locations lead to disorientation and unrealistic [6, 37]. It is for this reason that, from the mentioned techniques, Teleporting was often considered the least immersive, despite its efficiency and user preference [13]. Motion-based implementations of this technique, such as Point-and-Teleport, however, have mitigated this [8], which supports the next conclusion.

Locomotion techniques reliant on artificial means of input, such as controllers, are less suited for providing high levels of presence in a VE, compared to motion-based techniques. The lack of the appropriate proprioception feelings during navigation hinders immersion and may also result in cybersickness if the motion in the VE is continuous [27, 37]. Motion-based techniques, on the other hand, support higher feelings of presence, at the cost of ease-of-use [6, 11, 38, 39, 54].

With the explored literature it is also possible to conclude that the more a Motion-Based technique resembles real walking the better it grades in immersion levels [54]. An identified problem created by these techniques is the lack of physical space to map a walkable extensive VE [11, 38, 39]. Walk-In-Place and Arm-Swinging present accessible solutions to this problem, yet their representations of walking are not the most accurate [11, 39]. ODTs provide a more similar feeling to natural walking (even if not perfect), but are not suited for use-cases in which the more complex set-up is to be avoided [11, 54]. RDW techniques resort to actual Natural Walking for locomotion, scoring high in immersion, yet this varies with the type of redirection being applied. As seen in the Redirected Walking section, these techniques can employ different types of redirection, and some of these are more overt than others [38, 50]. Imperceptibility seems to be the key aspect of a redirection technique that strengthens feelings of presence created by the naturalness of walking.

From these conclusions RDW proves to be the best route for this research, as its applicability is extensive and highly variable, and is the most suited for VR applications that prioritize high immersion. Our implementation then needs to resort to redirection techniques that focus on maximizing the feelings of natural motion, and mitigate the overtness of the techniques.

2.3 Non-Euclidean Spaces in VR

As discussed in the Navigation of Virtual Environments section, navigation employs mental effort, mainly through the act of intake and keeping of spatial information, which is supported by the use of the denominated cognitive/mental maps [14]. Being a mental representation of spatial data, its understanding is quite limited, although it is arguably instinctive to call it a "picture in our heads", yet studies as those of William Warren [57] reveal that this is inaccurate.

The experimental biology study done by Warren [57] defies navigation assumptions, by exploring Non-Euclidean spaces in VR. Our perception of the real world is bound to the rules of 3 Dimensional Euclidean Geometry, and thus Non-Euclidean Spaces refer to spaces in which these rules are altered or do not apply, being then bound to a Non-Euclidean Geometry. This section's purpose is to explore two varieties of Non-Euclidean Spaces and their use in VR: Impossible Spaces, which modify the geometric rules of distance, and Hyperbolic Spaces, which alter the Euclidean Parallel Postulate - given a line and a point not on that line, only one parallel line can be drawn through the point [40].

If one was to store spatial knowledge onto a Euclidean mental map, it would be conclusive that traversing a Non-Euclidean Space would prove to be disorienting, yet Warren's study proves the contrary [57]. In this VR experiment, two groups of users

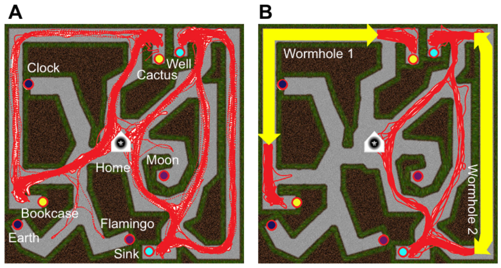

Figure 2.12: Traversed mazes in study by William Warren, where A is the "normal" Euclidean maze, whilst B is the Non-Euclidean maze with Wormholes that seamlessly translate a user from one location to the next. Red lines indicate the paths users took. [57]

had to traverse a maze, yet one group traversed the maze normally whilst the other traversed a maze with the inclusion of invisible wormholes that seamlessly transported them from one position to another creating a Non-Euclidean Impossible space, as seen in Figure 2.12. The mazes contained objects and the two tasks of the study consisted on firstly finding the objects and the routes between them, and then participants were asked to go one object to another in the shortest route possible without the mazes' structures, relying only on their spatial knowledge. The results on Figures 2.12 and 2.13 show that the participants of the Non-Euclidean maze revealed a clear bias towards the use of the wormholes. Warren states that these results are in agreement with his hypothesis that spatial knowledge is represented as Cognitive Graphs, rather than Cognitive Maps, since despite the irregularities caused by the wormholes, participants consistently relied on local metric cues and graph-like relational behavior.

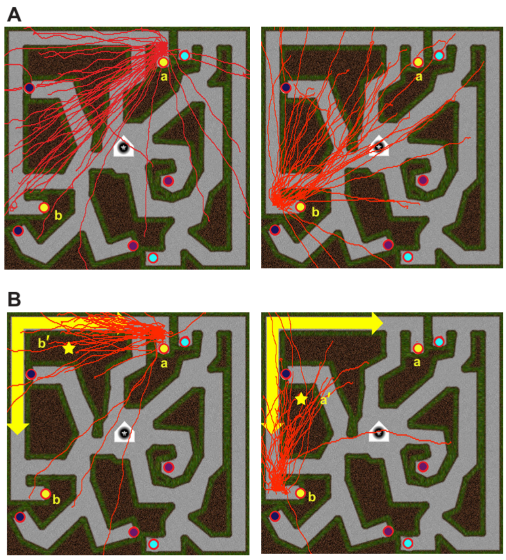

Figure 2.13: Paths taken between objects Bookcase and Cactus in Euclidean maze A and Non-Euclidean maze B. Stars in maze B indicate the location of the object in Non-Euclidean coordinates. The dense amount of paths in the direction of these stars show that participants' Wayfinding was highly biased by the Wormholes. [57]

With this demonstration, it is conclusive that Non-Euclidean Spaces are primed for VR use. In the next sections, the advantages that this type of spaces have for RDW will be explored.

2.3.1 Impossible Spaces

Fictional works such as the science-fiction TV show from BBC *Doctor Who* include spaces that defy the physical laws of our reality, such as the TARDIS, the iconic spaceship that is "bigger on the inside", to increase the sense of wonder in their narratives. It was not long after the "second-wave of VR development" [2] that fans of the show tried to recreate this feeling of wonderment by bringing the famous police box to life through the use of VR, due to its immersive capabilities [7] . This project and the previously mentioned study by Warren [57] are prime examples of what Impossible Spaces are and their general application in VR

Impossible Spaces are, in the majority of cases [33], experiences taking place in VEs that violate the rules of Euclidean Space, yet keep the appearance of the real world by keeping most of its Euclidean Geometry intact. This creates large VEs that are essentially multiple Euclidean spaces that look ordinary when experienced locally, but when their topology is inspected, it is clear that these spaces are connected in a manner that is physically impossible. This creates the often called "Self-Overlapping Architectures" [33, 52].

These VEs capitalize on the lack of physical restrictions to create an architecture that fits within physical tracking spaces, granting users the ability to naturally walk in a much larger VE by redirecting users away from the edges of their tracking space [16, 52, 56], hence the use of Impossible Spaces is considered a form of RDW [38]. Given that RDW is a highly immersive method of locomotion, due to the walking motion it employs, as

[7] TARDIS VR by itch.io user *feroxxy* - https://feroxxy.itch.io/tardisvr - Last Access: Jan 2025

Figure 2.14: A screenshot of the TARDIS VR project, depicting the famous police box that is "bigger on the inside", one of the possible ways to depict an Impossible Space in VR.

seen in the previous Redirected Walking section, in conjunction with the fact that users perceive the local environment as a Euclidean space, since distance perception is accurate by norm [4], Impossible Spaces provide a highly immersive VR experience.

The illusion of the self-overlapping architecture is mostly unnoticeable, especially when users are naive to the manipulation at hand [52]. Distractors, visual and auditory feedback, and contextual environmental events are potential auxiliary methods to raise the VE's level of immersion [12, 16], since these methods help lower the overtness of the redirection that is taking place.

VR applications typically use two main methods to connect the various sections of a Self-Overlapping Architecture:

- **Transitioning Areas** - Transitional spaces that link different sections by recurring to the previously discussed "change blindness" redirection technique. These areas are usually curved corridors that restrict users' FOV, allowing for the mentioned changes to happen without the users' knowledge [51, 55] (Figure 2.15).

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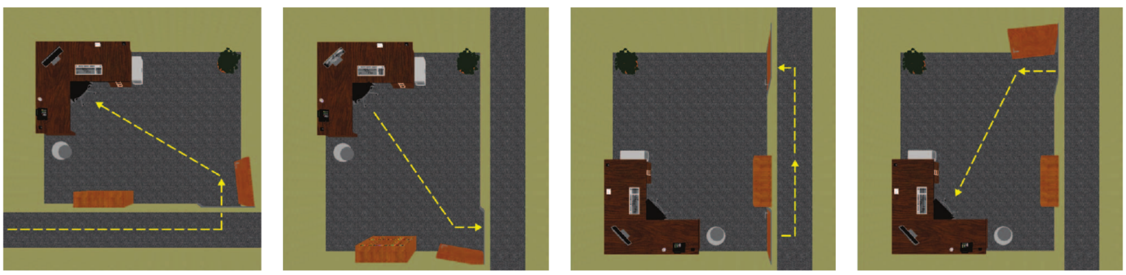
- **Portals** - As discussed in the Redirected Walking section, the instantaneous teleportation caused by Overt Discrete Repositioning RDW techniques could be highly disorienting if the user is not prepared or does not have the context for such repositioning. Portals help mitigate the overtness of this technique, serving as preview to the location the user is going to teleport to after passing through it [17]. The transition between the locations can be seamless, such as the wormholes from the previously mentioned study by William Warren [57], making the teleportation even less noticeable, and therefore, more immersive. The "Non-Euclidean Worlds Engine" project [8] provides several examples in which these portals might be used (Figure 2.16).

The use of Impossible Spaces presents as a solution to map a large VE into a limited physical tracking space, and its applications with RDW techniques seem to be extensive,

[8] Video on the "Non-Euclidean Worlds Engine" by *Code Parade* - https://youtu.be/kEB11PQ9Eo8 - Last Access: Jan 2025



(a) The user enters a 14' x 11' room and walks towards a desk to view the computer monitor.

(b) When the user approaches the monitor, the corridor and the door to exit the room are instantaneously rotated by 90 degrees.

(c) When the user enters the hallway, the second doorway is added, and the contents of the room are swapped with the next room.

(d) The first door is removed as the user enters the second room. The process can then be repeated.

Figure 2.15: A step-by-step explanation of a possible implementation of change blindness redirection through the use of a Transitioning Area. [51]

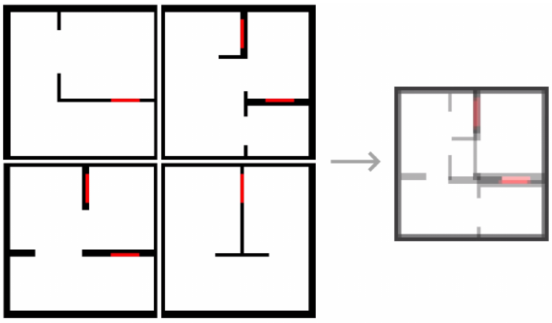


Figure 2.16: A visual representation of a self-overlapping architecture from the "Non-Euclidean Worlds Engine" project. The four separate rooms (left) are merged together (right) through the use of portals represented in red, compressing them into a VE that only requires a physical space four times smaller than the one occupied by the four rooms.

all depending on the context and needs the VR application is being developed. Flexible Spaces, developed by Vasylevska et al. [56], serves as an example of how extensive these possibilities can be, as it is a combination of the mentioned techniques, that in conjunction with *Procedural Content Generations*, creates an all-in-one dynamically adjustable redirection technique.

2.3.2 Portals

As discussed in Section 2.2.5, the instantaneous teleportation caused by Overt Discrete Repositioning RDW techniques can be disorienting if users are not provided with an appropriate cue. Portals address this issue by acting as gateways between distant points in a self-overlapping Impossible Space, offering a preview of the connected environment and cueing users that they may be transported to the displayed destination by stepping through the portal [17, 22, 31, 33].

Portals are most prevalent in the video game scene [35], brought to popularity by the

Figure 2.17: In the video game *Portal*, players must solve puzzles using a pair of connected blue and orange portals. In this example the preview capabilities of portals is displayed, as it is possible to see the previews of the orange and blue portals.

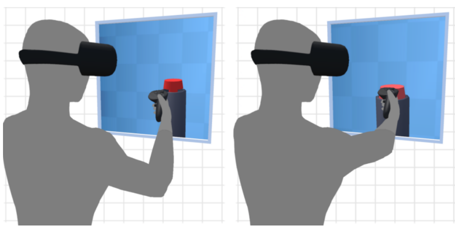
2007 game *Portal* from *Valve* [9], however research on the use of portals in VR applications is still ongoing. In VR research, various iterations of portals have been developed and researched for various functions, such as:

- **Redirected Walking** - A common use for portals in VR relies on their use for RDW. Comparitive works such as those by Lochner & Gain [33] and Rebelo et al. [44] recur to the use of portals as a means to compare Natural Walking locomotion using portals and other means of VR locomotion. Usually door-shaped, these portals connect various points in a self-overlapping Impossible Space, compressing the VE into the limited physical tracking space, allowing users to naturally walk through the environment (Figure 2.16).

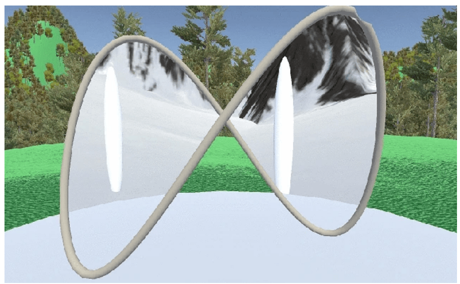
- **Extended Reach** - Window-shaped portals have been used as a means to extend reach, enabling users to reach to otherwise unreachable objects blocked by distance or obstacles [20, 1]. Variations include the ability to move the portal in real-time [1] and having a mirroring functionality [30].

- **Visualization/Comparison** - Portals may also be used to compare or visualize VEs that are irreproducible in the real world. This has been done through the use of

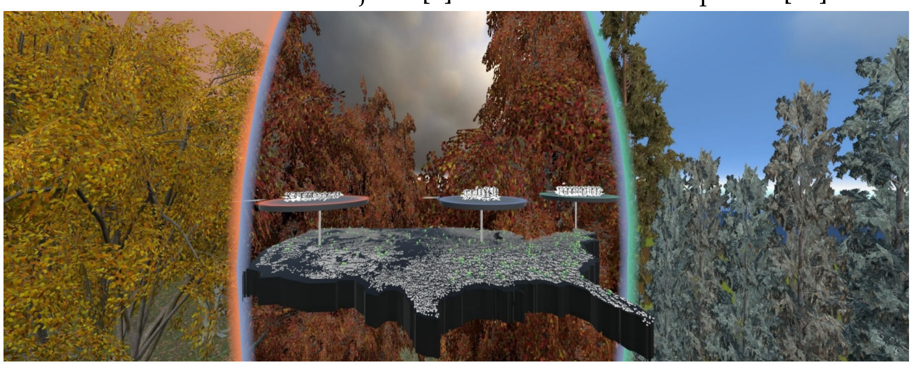
[9]Portal Steam page - https://store.steampowered.com/app/400/Portal/, Last Access - Aug 2025



(a) Portals may be used to extend users reach, creating a window that allows users to interact with distant objects. [1]



(b) Portals may be used as a means to explore complex topological structures, such as this knotted portal. [53]



(c) Portals have also been used as a means to compare different worlds through juxtaposition, such as forestry data. [36]

Figure 2.18: Multiple portal applications in VR.

volumetric wedges, that allow the comparison of multiple virtual worlds through juxtaposition [36], and the use of portals constructed from knotted curves that offer a novel way to explore complex topological structures [53].

The aforementioned portal variants share the use of a stereoscopically rendered plane, which provides a preview of the destination space and enables a seamless transition from the entry to the destination portal. A common method of rendering this preview is through the use of stencil buffers [35], which can be thought of as a 2-dimensional arrays that are the same size as the user's screen. Each portal has an associated camera that is placed relatively with the user's camera and the opposing side of the portal, as if the user position was mirrored. Thus, both the position and rotation (and scale if the paired portals have different scales) of the camera must be modified accordingly.

The rendering of a scene through the stencil buffer approach is done recursively. The buffer stores the recursion level of each pixel, corresponding to which level of "depth" it is (0 - user's view; 1 - portal in the user's view; 2 - portal inside a portal in the user's view; etc.). When rendering the frame, the algorithm goes through each recursion level, only rendering the pixels equivalent with said level with the corresponding camera. As such, the method starts by rendering the pixels outside a portal through the user's camera, then it renders the portal's view through the portal's camera, and so on for all recursion levels. Figure 2.19 exemplifies a simplified version of a stencil buffer.

Another common approach for rendering portal views is through the use of pre-rendered textures. It involves placing the camera as described above, however, rather than rendering the view as the previous method does, it saves it into a texture and places the pre-rendered texture on the portal. Although a simpler approach, this method does not supply the same visual fidelity as through the use of stencil buffers.

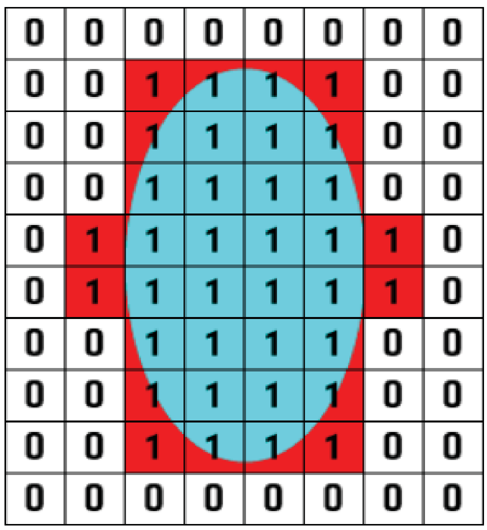


Figure 2.19: A simplified representation of a stencil buffer when rendering a portal. The inner oval contains multiple pixels with a recursion depth of 1, that represents the portal.

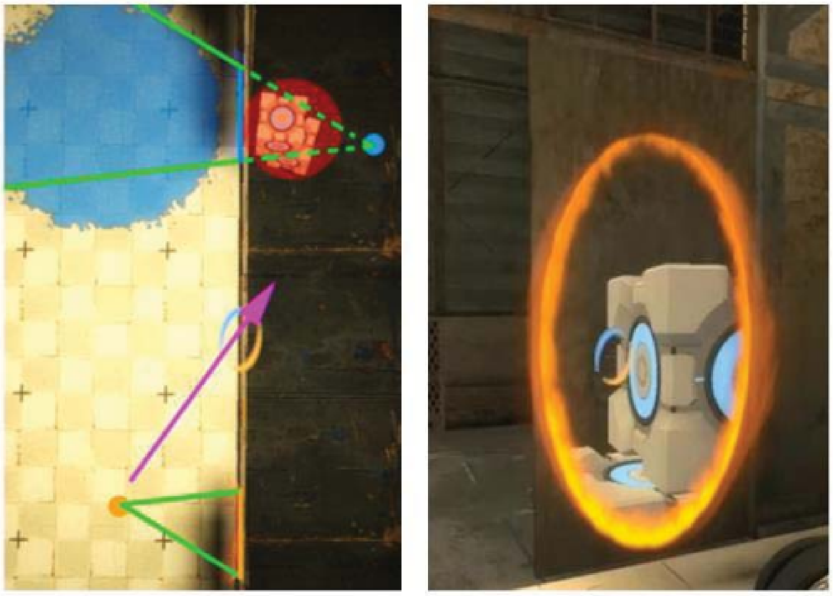


Figure 2.20: The "banana juice problem" occurs when there are objects between a portal and its associated camera for rendering the preview. To solve this issue, the camera must clip(not render) any of the objects or structures between the camera and the portal. [35]

A common problem for both these rendering methods may occur as the result of having objects between the portal and the camera's view, named the "banana juice problem" [10]. This results in unorthodox view through the portal, solved by not including the objects when rendering, also known as *clipping*.

2.3.3 Hyperbolic Spaces

Hyperbolic Spaces acabaram por não serem utilizados. Vale a pena manter esta subsecção para contexto no trabalho preliminar?

As stated before, Non-Euclidean Geometry is a variant of Euclidean Geometry by having its axioms changed, one of them being Euclid's Parallel Postulate. It states that through any given point not on a line there passes exactly one line parallel to that line in the same plane [26]. If one were to change this axiom to either permitting the existence of two or more parallel lines or restricting it to no parallel lines, they would get Hyperbolic and Elliptic Spaces, respectively [40].

Hyperbolic Spaces are then infinite by definition, having more space available in a given distance than in Euclidean Spaces, presenting a constant negative curvature [40]. Its properties make it valuable for the representation of relational data, as its infinity allows integrating trees of data with deliberately large sizes, proving more useful than Euclidean Graphs [25, 32]. An example of this is the hyperbolic graph of most used languages in GitHub, created by Celiska et al. [10] and represented in Figure 2.21, in which the distances between the language nodes indicated how frequently these programming languages were used together.

[10] CS50's Introduction to Game Development 2018; Lecture 11- https://youtu.be/ivyseNMVt-4, Last Access - Aug 2025

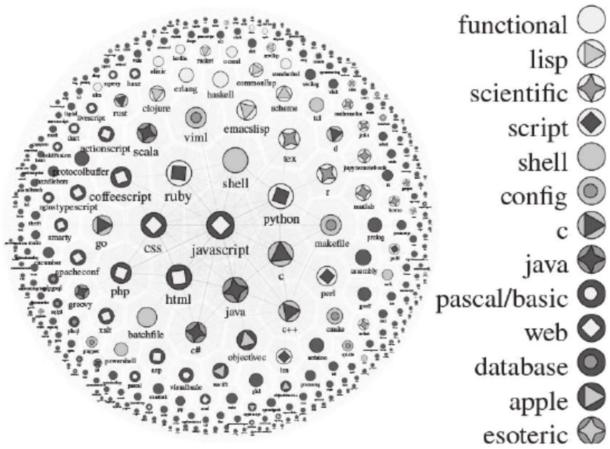


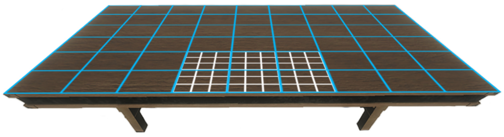
Figure 2.21: Hyperbolic graph of GitHub's most used languages. The closer the language nodes are, the more frequently these languages are used together. [10]

Entertainment has also benefited from Hyperbolic Geometry in the video-game industry, as games like *Hyperbolica* (Figure 2.22) [11] and *HyperRogue* [25] have integrated hyperbolic spaces into their gameplay to create challenging puzzles and situations for players to solve. With the seamless integration of Hyperbolic Spaces in video games, it could be reasonable to assume that these would translate well into VR. The literature on the matter, although not complete, is extensive enough to confirm that there is an interest in researching this topic.

The visual tool by Hart et al. [21] is an example on this interest, as they aimed to create a VR experience that allows users to more intuitively grasp Hyperbolic Geometry. Various models were used to simulate this space, and the application permitted users to

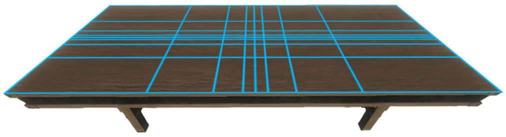
[11] Hyperbolica Steam page - https://store.steampowered.com/app/1256230/Hyperbolica/, Last Access - Jan 2025

Figure 2.22: A screenshot of one of the levels from the game Hyperbolica.



(a) The resultant mappings of linear functions: x for white and $3x$ for blue lines.

(b) The resultant mapping of the hyperbolic tangent function (*tanh*).



(c) The resultant mapping of the inverse hyperbolic tangent function (*arctanh*).

Figure 2.23: The four mappings studied by Rebelo et al. [45]

navigate through the VE, which proved a challenge. Due to the space's negative curvature, phenomena as *holonomy* - a result of parallel transporting vectors along a closed loop - occurs, which can make Hyperbolic Spaces highly disorienting, since it translates into effects, such as the floor appearing to move away or rotate. Authors purposed methods of solving this issue, though they were recognized as artificial means that "hack" the simulation.

Rebelo et al. [45] have also conducted research on the use of Hyperbolic Spaces in VR. One of the studies conducted in this work pretended to examine how users would react to different mappings between virtual and physical spaces, using tangible objects on a table that users had to move and rotate. The four different mappings (Figure 2.23) were either mapped by linear functions - correspondent to Euclidean Spaces - or Hyperbolic functions - correspondent to the Non-Euclidean Spaces - in this case the hyperbolic tangent and its inverse, morphing space so that the center of the table occupied more or less space, respectively. Results revealed that there were no significant differences in terms of efficiency between two linear and hyperbolic scenarios, and the research concluded that users were able to adapt do Hyperbolic Spaces quickly, going in accordance with the previously mentioned work from Hart et al. [21] and study by Pisani et al. [40]

2.4 Summary

In summary, this chapter has introduced concepts of VR, and how VEs are constructed and navigated, in order to have the base context of what locomotion techniques are and how they affect VR navigation.

As such, various locomotion techniques were explored, addressing how their characteristics differ from each other and hence have different strong points and limitations. Since the objective of this work is to contribute to immersive navigation, it was concluded that RDW techniques were the most indicated, as these techniques employ continuous motion through natural walking, achieving higher feelings of presence in the VE, compared to other techniques.

The limitations of RDW were also addressed, as naturally walking in a constricted physical space is still a challenge in the implementation of these techniques. Our work addresses this challenge by employing redirection through the use of non-Euclidean VEs, thus non-Euclidean geometry and its applications in VR have been explored in this chapter as well. The particular examples of non-Euclidean spaces explored were Impossible and Hyperbolic Spaces, as these allow natural walking in large VEs whilst in limited tracking spaces.

3

Analysis and System Architecture

In order to explore the impact of portals with continuous previews on Virtual Reality (VR) navigation and User Experience (UX), we developed four portal variants for evaluation in a user study. To support this development and study, a functional system was required. This chapter explores the design and concepts necessary for the creation of said system, establishing the foundation for addressing the Objectives and Research Questions outlined in Section 1.2.

Dar um resumo do que será falado.

3.1 Requirements

This research proposes the study of four VR locomotion techniques based on portals in a Non-Euclidean environment examining its impact on navigation and User Experience (UX). It was essential to create a VR experience within a Non-Euclidean Virtual Environment (VE) that relied on the use of portals for locomotion, paired with a suitable simple task that demanded users' to navigate throughout the environment using the developed techniques.

The system was designed to create a VE that supports natural walking and hand-tracking to maximize feelings of presence and immersion. Users perceive the world through a Head-Mounted Display (HMD) that is simultaneously tracking their movement in the physical environment, as well as their hands through the cameras present on the face of the HMD. The hand-tracking is used for interacting with the VE, whether it be for interacting with the portals, allowing users to navigate, or to interact with elements of the study's task.

During the conceptualization of the portals to be developed a study was conducted comparing Teleporting with Walking with Portals in VR which led to the submission and publication of an article for ACM Multimedia 2025 [**<empty citation>**]. The study took place in a virtual apartment, where participants were first asked to explore and then to complete an object fetch-quest, using one technique at a time. The study identified a key trade-off between the portal's distance from the wall and the clarity of the next-room preview. To ensure that users can safely turn 180 degrees after passing through without leaving the tracked play area, the portal must be positioned at least 60–80 centimeters away

já dá para citar o artigo?

from the virtual wall. However, this requirement introduces an awkward "dead space" and creates a design conflict. Placing the portal closer to the wall conserves physical space but limits the preview to little more than a wall and a narrow strip of floor. In contrast, positioning the portal further away offers a broader, more informative view of the next room, but does so at the expense of valuable room space and at the risk of appearing unnatural, like a floating frame. With this in mind, our solution required to approach these limitations.

In summary, the main requirements of our solution are as follows:

- Allow users to navigate the entirety of the VE solely by naturally walking in a limited physical tracking space (similar to the available space of common VR users, thus around 2.4 x 2.2 meters[3, 31]).
- Include variants of portal techniques that address the limitations caused by their placement and lack of preview.
- Include a common portal technique as a baseline for comparison with the variant techniques.
- Support interaction with the VE through hand-tracking, for interacting with portals and the task to be performed during the study.
- Include a task that incentivizes users to explore the entirety of the VE.
- Task design should be simple enough to be repeated with different locomotion techniques without introducing task-specific biases.

3.2 Case Study

A case study was designed in order to address the aforementioned requirements and investigate the proposed research questions. With the goal of studying the usability of portal variants with continuous previews as VR locomotion techniques in a small physical space (about 2.5 x 2.5 meters), an interior VE with a self-overlapping architecture was chosen as the experimental environment.

As such, the case study was designed as a museum experience, serving as an interior VE that can be contained in a constrict physical tracking space through the use of a self-overlapping non-Euclidean virtual space. This setting also permits a more natural selection of exploratory and immersive tasks that rely on the use the developed locomotion techniques. The chosen tasks were associated with exposition items and artworks present in the museum, gearing users toward exploring the whole environment and feel present in the experience.

The multiple rooms of the VE should be connected through the portal techniques, creating the self-overlapping architecture. In the interest of analyzing the experience from each portal separately, the environment should be divided in as many sections as the number of portal variants, one for each variant, that should have the same room layout and the same tasks in order to ensure the validity of comparisons.

Throughout the case study users wear a HMD and naturally walk around the physical environment of 2.5m x 2.5m. To interact the HMD should capture users' hand movements through hand-tracking. Hand-tracking was opted instead of controllers in order to maintain the highest levels of presence possible. All users should experience all portal variants in order to accomplish a within subject comparison, hence users should sequentially experience all the sections of the museum.

The procedure for the case study follows a structured sequence of tasks that is repeated in each section. First, participants explore the assigned museum section using one of the portal variant techniques, interacting with the exhibited items. Once the section has been fully explored and participants have experienced the locomotion technique, an evaluation task is administered. Afterward, participants proceed to the next section, where the same sequence is repeated with a different portal variant.

With this case study it is possible to meet the requirements necessary to investigate the research questions in a controllable environment, ensuring that the constraints of a limited physical space are respected while allowing systematic evaluation of the proposed portal variants. By employing a within-subject design, a uniform task structure, and consistent room layouts, the study ensures comparability across techniques and supports the collection of reliable data on usability, presence, and user experience.

3.3 Architecture and Technologies

To develop the case study, it was necessary to define an architecture that could address the aforementioned requirements and research questions. The proposed system and the tools used to create it are presented in Figure 3.1, divided by their function: input, processing and output.

A foundational VR application was required to construct the VE, which in turn necessitated the use of a game engine. **Unity** was the chosen tool for creating the application, as it is widely adopted in both industry and research for VR development and provides a wide range of assets and plugins. To further abstract and simplify the integration with VR devices, we resort to the **OpenXR SDK**, providing and additional layer of abstraction that enables compatibility with a wide range of VR devices.

Using the **Unity** game engine with the imported **OpenXR Plugin** the process of creating an interactive 3D VE was simplified and streamlined, since these create the possibility of composing the environment with **C# scriptable objects**. This allowed the implementation of the portal techniques and the UI elements needed for the study's tasks, as well as a streamlined integration of these implemented objects into the VR application. The **XR Interaction Toolkit (XRI)** and **XR Hands** Unity packages were imported as Unity packages, further streamlining the implementation of the interactable elements of

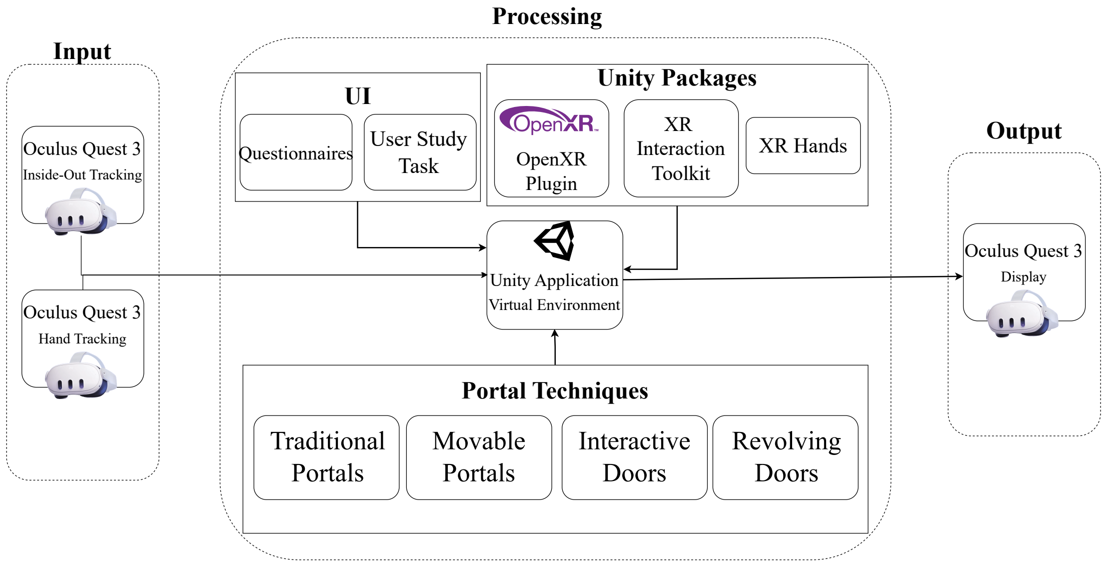


Figure 3.1: Architecture overview.

the application, by providing a high-level framework for interactions and hand-tracking support respectively.

Finally, to receive the inputs that affect the interactive VR application and display the effects of said interactions, a HMD was needed. We opted for the use of the **Oculus Quest 3** HMD, as it supports the most desired functionalities for the proposed case study: inside-out tracking for tracking the users' position in the VE, hand-tracking via its front-facing cameras for more immersive interaction, and a high-resolution display for visualizing the VE.

By combining these tools and structuring this architecture it is possible to meet the requirements of this case study: create a self-overlapping VE using different portal techniques, explorable through natural walking and interactable through hand-tracking technologies.

3.4 Preliminary Experiments

Complete according to space

3.5 Portal Designs

This study aims to explore and study variants of VR locomotion techniques based on natural walking with portals. As such, we propose three portal implementations that address the limitations of commonly used portals in VR research and applications, namely the lack of a proper preview when portals are placed closed to the limits of a VE and the unnaturalness caused when portals are placed further away from these limits.

This section presents the design choices underlying the four portal techniques examined in our user study: Traditional Portals, serving as the baseline condition representing

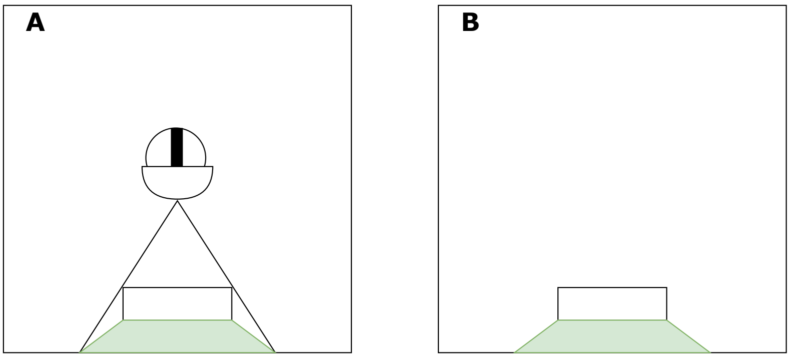


Figure 3.2: Representation of the limitation of Traditional Portal previews: The closer the portal is to the limits of the VE the observable preview diminishes, often revealing only a narrow segment of the connected space.

the commonly used portals in VR research, and the three proposed variants — Movable Portals, Interactive Doors, and Revolving Doors.

3.5.1 Traditional Portal

Our baseline condition represents the conventional approach to portals in VR, commonly seen in both commercial applications and academic research. Appearance-wise a door frame-shaped portal was chosen, both for its similarity to those used in prior research and for its association with the familiar real-world concept of doors.

The preview capabilities of this type of portal are, thus, the same as the ones commonly found in VR research and applications. As such, it is possible to evaluate the limitation of this type of preview when used in VR applications that resort to natural walking as a means of locomotion when compared to the proposed portal variants. Figure 3.2 represents the core challenge of traditional portals addressed by this work.

The level of interaction with this portal is minimal, as to use it the user must simply pass through the frame. As such, since the limits of the VE correspond with the limits of the physical environment, these portals should be placed within a distance of circa 80cm
check value
from the borders of the VE, so that users don't reach the physical limits of the tracking space. This portal placement further explores the limitation of these portals, as to use them users have to either: (1) go through the portal with a minimal preview and move around it in the destination room, (2) or move around the portal in their current room, obtain a better preview of the destination room and finally go through the portal (see Figure 3.3). Either of these options, however, causes the user to complete a 180-degree turn, redirecting them towards the center of the available physical tracking space.

3.5.2 Movable Portal

The Movable Portal's design addresses the wall clearance issue by allowing users to dynamically create the necessary space for transition. The main goal of this design is to provide user's a higher sense of control over the amount of space portals take, while additionally providing a better preview of the rooms that these portals are connected to. This is achieved by having the portal initially placed against the wall, with a reversed preview that renders the connected room as if it was positioned in a continuous space, instead of a self-overlapped space. Users can then move the portal when they wish to go through them, reversing the preview to the same manner it is rendered on Traditional Portals.

Thus, the designed interaction with this portal would go as follows:

1. Portal is against the wall, rendering a continuous preview into the connected room.
2. After accessing their destination, the user decides to go through this portal.
3. The user grabs the portal using their virtual hands. As they do, a valid placement area is rendered, indicating the user where they may place this portal.
4. After choosing their pretended placement, the user lets go of the portal. If the portal is positioned within the bounds of the valid area, it is placed and the preview is reverted according to the self-overlapped architecture. Otherwise, the portal reverts back into its original position against the wall with a continuous preview.
5. If the portal is correctly placed, the user may seamlessly transition to the connected space by moving through the portal.

Although the main goal of this design is to empower users with a strong sense of control, the valid area was created in order to have a failsafe measure against portals

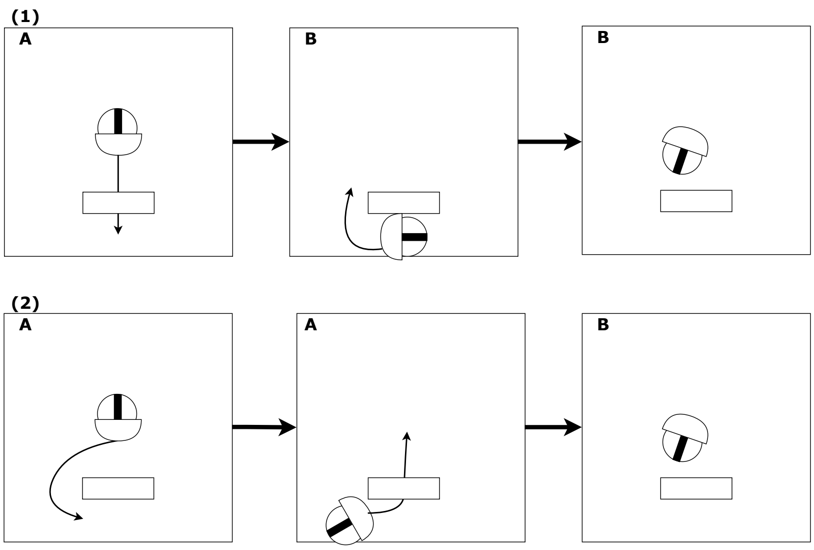


Figure 3.3: Two possible approaches to transition using Traditional Portals. (1) Users can go directly through the portal, with a minimal preview before transition, (2) or move around the portal to first get a proper preview of the room before transitioning.

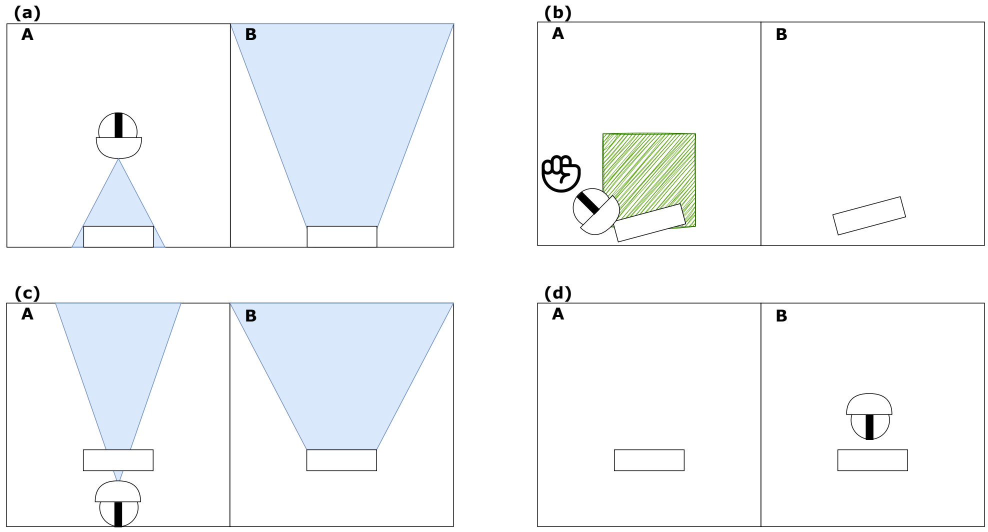


Figure 3.4: Interaction design of the Movable Portal: (a) At the start of the interaction the portal is placed against the wall with a reversed preview for a continuous appearance. (b) The user can then grab the portal with their virtual hands, which will prompt a valid area to render. The associated portal will follow the placement of the portal. (c) The user can then let the portal go within the bounds of the valid area, placing the portal and reverting the preview. (d) The user can then go through the portal.

overlapping with other objects in the environment. It was also necessary to reverse the preview when the portal is place, since if the preview was kept, the transition would cease to be seamless, as the preview would not correspond to the position the user would be transitioning to.

The Movable Portal's appearance was designed similarly with the Traditional Portal's design, being presented as an empty door-frame. However, it differs itself from the Traditional Portals by having a handle-like affordance to signal users that the portal should be grabbed in order to complete the interaction.

3.5.3 Interactive Door

The Interactive Door's design prioritizes naturalism by modeling the portal after a familiar real-world object: a door. The main goal of this design is to maximize immersion and intuitive use by leveraging users' everyday experience with doors, while simultaneously providing a reliable solution to the wall clearance issue.

Initially, the Interactive Door is transparent, offering a continuous preview of the adjacent room. This choice supports exploration by allowing users to perceive the contents of the next room before committing to interaction. As the user approaches, however, the door becomes opaque, prompting users to interact with it in order to complete the transition. After opening the door, similarly to the Movable Portal, the preview reverses to correspond with the self-overlapping architecture.

The interaction sequence can be summarized as follows:

1. The door is placed against the wall, transparent, rendering a continuous preview into the connected room.

2. As the user approaches the door, its surface becomes opaque, signaling that interaction is required.

3. The user reaches out with their virtual hand, grabs the handle, and performs a swinging motion to open the door, closely mimicking real-world behavior.

4. As the door swings open, the portal accompanies the door-frame. The preview is discreetly reversed.

5. Once the door is sufficiently open, the user may seamlessly transition into the connected room by walking through the doorway.

This interaction design achieves several objectives simultaneously. Firstly, the rotation of the door provides the necessary clearance from the virtual wall, ensuring that users are redirected into their available space by turning in a 90-degree angle. Secondly, the portal's door-like appearance is designed to convey a more natural and easy interaction, by emulating the act users do on a daily basis in the real world. Finally, the opacity change permits to covertly change the preview of the portal, allowing the portal to render a continuous preview when against the wall, and then rotate to match the self-overlapped space when opened.

3.5.4 Revolving Door

The Revolving Door's design explores a more continuous and guided form of transition, employing the metaphor of a revolving door to manage both the physical and virtual reorientation of users. Similarly to Interactive Door, the appearance of the Revolving Door changes dynamically based on proximity. From a distance, the door is transparent, allowing the user to preview the next room through a portal that renders a continuous preview to the next room, and as the user approaches, the door becomes opaque, concealing the preview and prompting direct physical interaction.

The intended interaction sequence is as follows:

1. The revolving door is integrated into the wall, initially transparent to provide a continuous preview of the adjacent room.

2. As the user approaches, the door becomes opaque, signaling that direct interaction is required.

3. The user steps into the door's compartment and begins pushing the door using their virtual hand.

4. As the door shifts to full opacity, the portal placed behind the door reorients by 90 degrees.

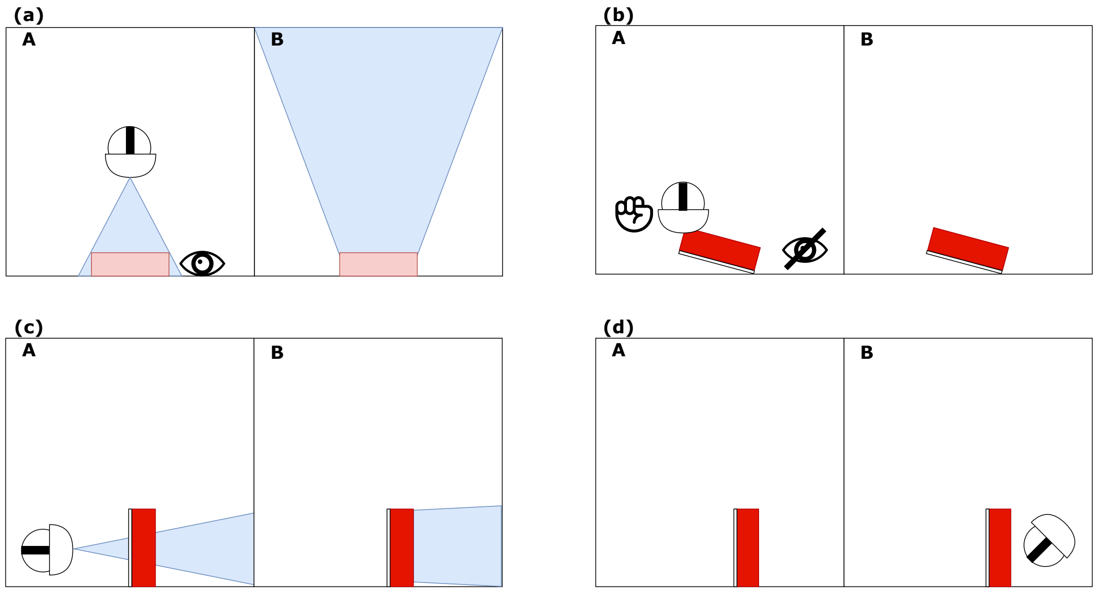


Figure 3.5: Interaction design of the Interactive Door: (a) From a distance the material of the door has low opacity, being transparent enough to reveal the portal behind it with a reversed continuous preview. (b) As the user approaches the door it becomes more opaque. When fully opaque, the user can grab the handle and swing the door open. (c) The door will open to a maximum of 90°, with the portal accompanying it throughout the motion. (d) The user can go through the portal to reach the connected room.

5. The physical motion of the door guides the user through a 180-degree turn, ensuring proper reorientation into the connected room.
6. During this movement, the user seamlessly passes through the perpendicular portal and emerges in the new space once the door has completed its rotation.

Although in a different type of physical interaction, this design achieves the same objectives as the previous variants. Firstly, the revolving mechanism provides the necessary clearance from the virtual wall by guiding the user through a 180-degree turn, ensuring they are correctly oriented towards the available space. Secondly, the door's appearance is designed to foster a more natural and intuitive interaction, as it builds on users' familiarity with a real-world object. Finally, the opacity change permits the system to covertly adjust the portal's preview: from a continuous preview when the door is at transparent, to a rotated preview that matches the self-overlapped architecture as the door turns during the transition.

3.6 Summary

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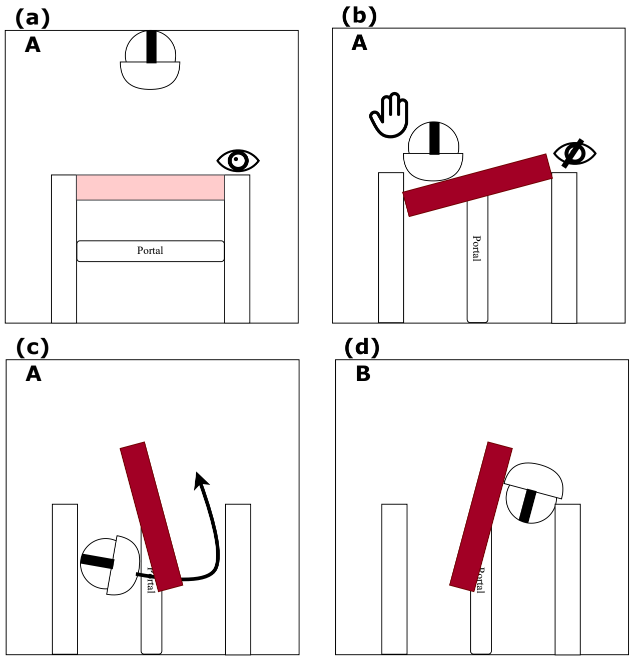

Figure 3.6: Interaction design of the Revolving Door: (a) From a distance the material of the door has low opacity, being transparent enough to reveal the portal behind it with a reversed continuous preview. (b) As the user approaches the door it becomes more opaque. When fully opaque the portal rotates 90°and reverts its preview. (c) As the user pushes the door, the door guides them to complete a 180°turn and to pass through the now perpendicular portal. (d) The user emerges from the other side of the door in the connected room.

4 Implementation

Having established and presented the requirements and design choices of the developed system, this chapter details the implementation of the concepts defined in Chapter 3.

Adicionar parágrafo resumo

4.1 Player

The VR application is designed with the player at its center, as the experience is mediated through their perspective and actions. For this, a dedicated player entity was implemented, serving as the bridge between the user wearing the HMD and the actions taken within the VE. The main components of this entity are illustrated in Figure 4.2.

As mentioned, the player takes center stage regarding the experience. The player entity contains a rig structure that manages the tracking of the HMD and its input devices, ensuring that these are synchronized with the application.

The hierarchy of the rig includes a head element, which in turn serves as the parent to the left and right eye elements. Each of these holds a virtual camera responsible for rendering the VE to the corresponding display in the HMD. Tracking data from the headset

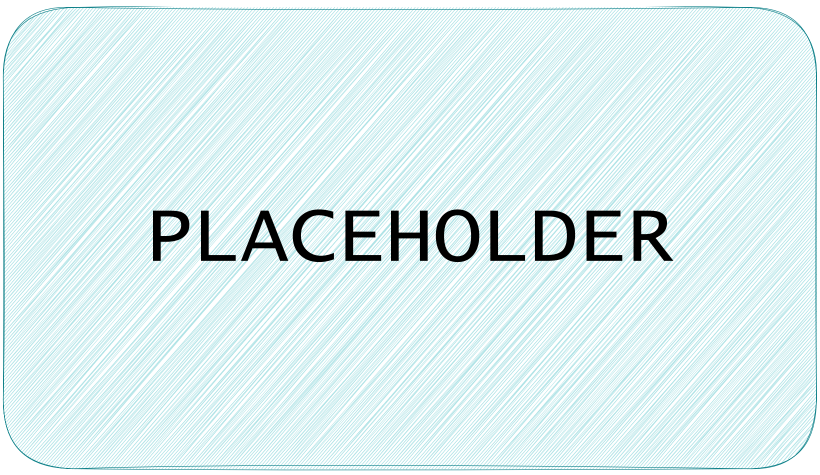

Figure 4.1: The composition of the Player entity

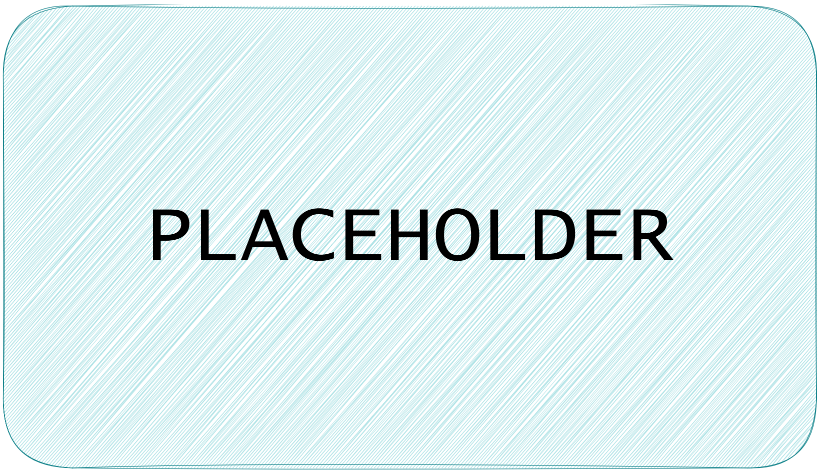

Figure 4.2: Depiction of the Virtual Hands used during the experience.

is translated into positional and rotational coordinates for these objects, supporting full 6 Degrees of Freedom (6DOF) movement.

To maximize immersion, the application was designed to use hand-tracking features as the primary method of interaction, rather than handheld controllers. Skeletal hand models are rendered and animated based on tracking data provided by HMDs with hand-tracking capabilities. Each hand includes an interaction component that enables the user to engage with virtual objects and interface elements, such as portals and menus, during the VR experience.

mudar fig

4.2 Portals

The portal implementation used in this work builds on the approach described by Lochner & Gain [33], which provided the foundation for the core portal functionality and accelerated the development of the designed portal variants. All the portals studied in this work recur to a base *Portal* script that handles the stereoscopic rendering of the portal previews, as well as the teleportation of objects through the portal.

The process of rendering the stereoscopic preview is consistent across all portal variants. As described in Section 2.3.2, the portal preview must replicate what a user would perceive if their position and orientation relative to the source portal were transformed into an equivalent position and orientation relative to the destination portal.

The implementation for this work adopts a texture-based approach, in which the space visible through the destination portal is rendered and projected onto the surface of the source portal. To achieve the stereoscopic effect, separate portal cameras are maintained for the left and right eyes, each generating a distinct view of the destination space (Figure 4.3). These views are then mapped to different rendering layers, ensuring that each eye perceives only its corresponding texture. Thus, all portal variants consist of two screen surfaces on which the textures are applied, as well as two cameras responsible

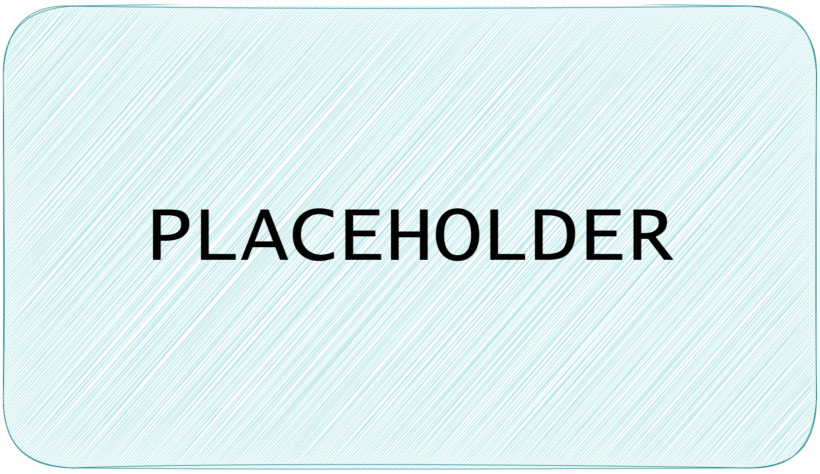

Figure 4.3: The positioning of portal cameras according to player position.

add overlap position explanation

for rendering the eye-specific previews.

A *PortalTraveller* script handles the behavior of objects capable of traversing through portals. When an object carrying this script enters the portal's bounds, the script is triggered and the object's position and rotation are recalculated relative to the destination portal, effectively teleporting it to the corresponding location on the other side. The calculation done to obtain the new position of the traveller is as follows, where $\mathbf{T}_{\text{traveller}}$ is the traveller's current transform (4×4 matrix), $\mathbf{M}_{\text{thisPortal}}$ is the current portal's world transform matrix and $\mathbf{M}_{\text{linkedPortal}}$ is the linked portal's world transform matrix:

$$\mathbf{T}_{\text{new}} = \mathbf{M}_{\text{linkedPortal}} \cdot \mathbf{M}_{\text{thisPortal}}^{-1} \cdot \mathbf{T}_{\text{traveller}}$$

Since the player entity also includes the *PortalTraveller* script, the coordinated use of the stereoscopic preview and the teleportation logic allows the transition through portals to appear seamless and continuous.

4.2.1 Traditional Portals

Traditional Portals, designed to serve as a baseline condition to be compared with the portal variants, correspond closely with the aforementioned core portal functions, as they provide no further functionalities. A representation of the portal is provided in Figure 4.4 and the composition of the components of this portal technique are present in Figure 4.5.

The portal screens correspondent to each eye, on which the stereoscopically rendered preview is rendered, are within a frame of 3D objects that hold no component other than their mesh renderers, serving simply as visual aid, as designed. Two cameras, one for each eye, are included as part of this object, in order to be used to render the stereoscopic preview onto the screens of the linked portal. Each of the screens is composed of only a plane mesh renderer, with materials whose shader maps the textures captured by the

Figure 4.4: The Traditional Portal.

cameras of the linked portal. Both these screens are parented by a game object that provides a trigger collider used to detect when users and/or objects containing the *PortalTraveller*.

A main *Portal* script component handles the logic that controls the positioning of the cameras, as well as the detection and teleportation of a *PortalTraveller* through the aforementioned trigger colliders, the rendering of the portal preview onto the screens and the linking between portals. The script provides a manual input of the portal that is to be linked with the portal that holds the script. With the portals linked, it is possible to calculate the positioning of the cameras using transform matrices. The equation for the positioning of each of the two portal cameras is:

$$\mathbf{T}_{\text{portalCamera}} = \mathbf{M}_{\text{thisPortal}} \cdot \mathbf{M}^{-1}_{\text{linkedPortal}} \cdot \mathbf{T}_{\text{eyeCamera}}$$

where:

- $\mathbf{T}_{\text{traveller}}$ = the transform in world space of the camera correspondent with the user's eye
- $\mathbf{M}^{-1}_{\text{linkedPortal}}$ = inverse of the linked portal's world transform
- $\mathbf{M}_{\text{thisPortal}}$ = current portal's world transform
- $\mathbf{T}_{\text{portalCamera}}$ = the transform of the camera used to render the portal view

Given the interaction design of this portal type, this portal does not change states at any point during the interaction, as users only pass through it to go to their pertained destination.

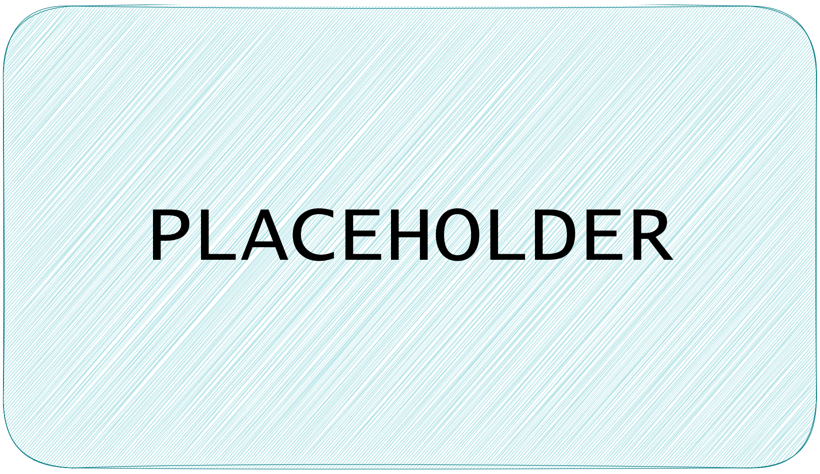

Figure 4.5: Traditional Portal components.

4.2.2 Movable Portals

The Movable Portal extends the functionality of the Traditional Portal, with additional features that allow it to be repositioned and placed within the environment, as described in Section 3.5.2. Figure 4.6 demonstrates the implemented interaction of the technique and the component structure of this portal technique is shown in Figure 4.7.

The elements of the Traditional Portal are fully maintained: the frame, the two screens, the two cameras, and the core portal script on the parent object. This variant differs by introducing two handles on the portal's frame, which include colliders to enable interaction. It also defines a valid area where the portal can be placed when grabbed. In addition to the base functionality, a dedicated *MovablePortal* script manages all behaviors related to the interaction with this portal, ensuring that its movement and placement follow the defined constraints.

The *MovablePortal* script component defines three distinct states for this portal: **1. Start** - when the portal is against the wall before being interacted - **2. Held** - when it is being held by the user - and **3. Placed** - when it has been placed in the valid area.

When the portal is placed against a wall in the Start state, it renders a preview of the connected space, similar to Traditional Portals. However, to create the illusion of a continuous space, the preview is mirrored along the y-axis. This is effectively done by spinning the portal 180 degrees on the y-axis, changing the $M_{\text{thisPortal}}$ matrix from the aforementioned equation and, by consequence, inverting the positioning of the cameras of the linked portal. The teleport functionalities of the *Portal* script are interrupted, preventing users from reaching the edge of their physical tracking space.

The transition to the 'Held' state happens when the user grabs the handle of the Movable Portal. Whenever a user does a grab/pinch gesture with their virtual hand while it is positioned within the collider of the handle, an Event is triggered, which in turn triggers the portal's transition to the 'Held' state.

In the 'Held' state, the position of the portal tracks the user's movement for as long

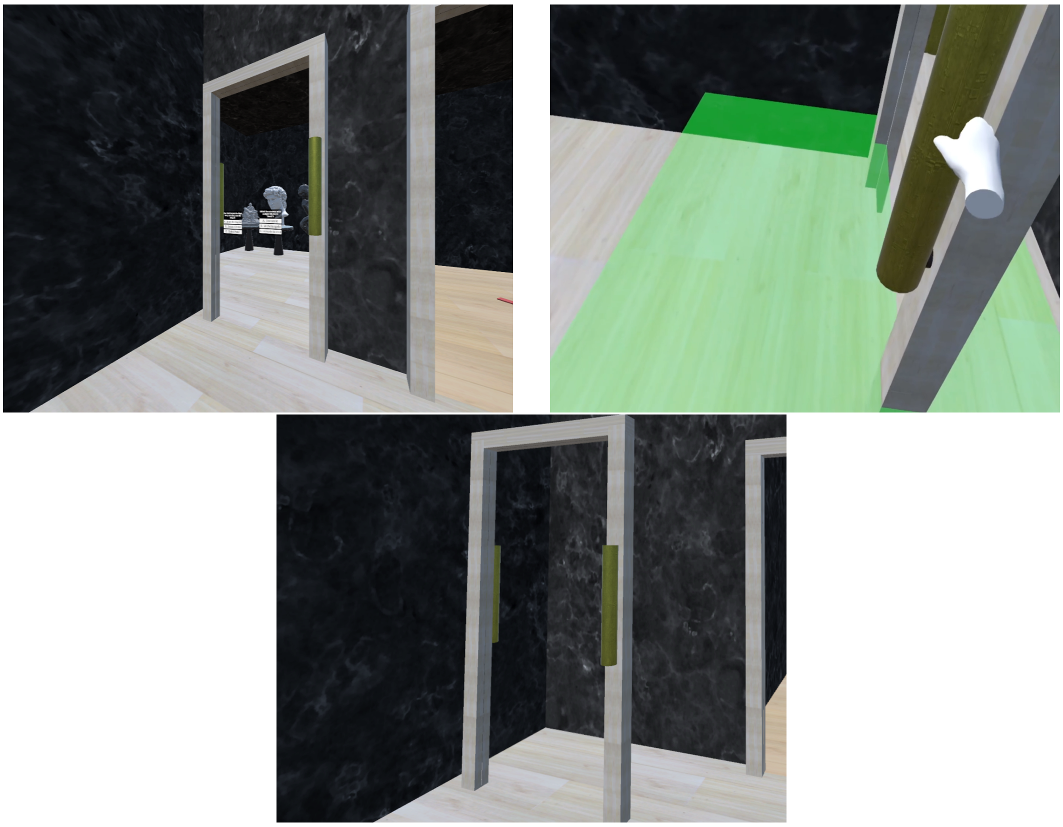

Figure 4.6: The interaction sequence for the Movable Portal: (a) Initially, the portal is placed against the wall with a rotated continuous preview. (b) The user grabs the portal with their virtual hand through the golden-handle. A green valid area is displayed to show the user where they may place the portal. (c) The user places the portal by letting go of the golden-handle. The preview rotates to match the position of the user.

as the grab gesture is maintained. Additionally, the valid area where the portal may be placed is also rendered and stays so for the duration of this state. To avoid accidental teleportations, the teleport functionalities of the *Portal* script remain paused, certifying users don't accidentally clip into the portal while holding it.

To place the portal and transition it to the 'Placed' state, the user must release it within the bounds of the valid area by ending the grabbing gesture. To verify if the position of the portal is valid, the following inequalities are used:

$$P \in \text{zone} \iff \begin{cases} |\, x_p - c_x \,| \leq \frac{w}{2} \\ |\, z_p - c_z \,| \leq \frac{d}{2} \end{cases}$$

where:

- $P = (x_p, y_p, z_p)$ is the point transformed into the local space of the zone: $P' = T^{-1}P$.
- $C = (c_x, c_y, c_z)$ is the center of the valid zone in local coordinates.
- w, d are the width (X-axis) and depth (Z-axis) of the box.

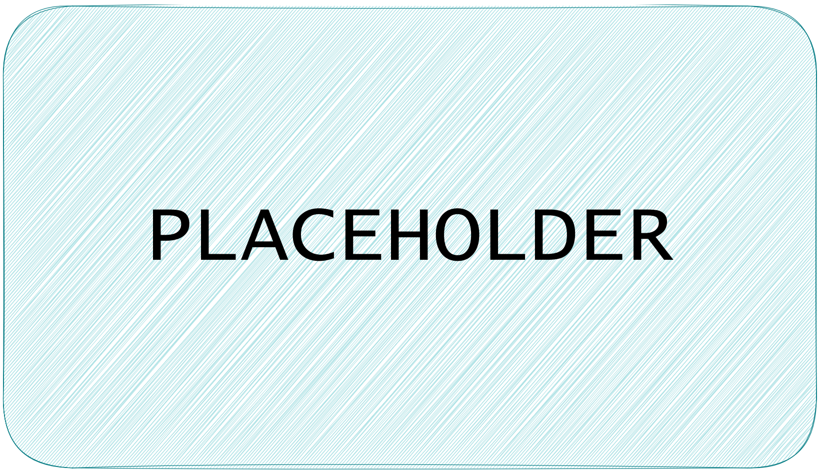

Figure 4.7: Movable Portal components.

If let go in an invalid position, the portal returns to the 'Start' state, returning to its starting position. Otherwise, if let go in a valid position, the portal transitions to the 'Placed' state. When 'Placed' the linked portal matches the position of the now placed portal in the x and z axis, so that they become overlapped. The rotation of both portals are matched as well, so that the preview reverts to the way it is calculated on Traditional Portals, in order to achieve a seamless transition. Once this alignment is complete, the teleport functionality of the *Portal* script resumes.

4.2.3 Interactive Door

The design of the Interactive Door prioritizes naturalism, being modelled after a familiar real-world object: a door. Its functionality extends the concept of a standard doorway by enabling dynamic interaction within the environment, allowing users to open and close the door at their will, manipulating the space it occupies in the environment in an intuitive manner. Figure 4.8 illustrates an example of the implemented interaction, while the component structure supporting this interaction is depicted in Figure 4.9.

Designed after real-world doors, the Interactive Door is composed of a doorway completed with a panel door featuring a golden handle. The two screens on which the preview is rendered are behind the door, nested in the hierarchy of the door object, so that the screens position follow the motion the door does when opening or closing. The portal additionally includes the two cameras necessary to render the preview of the linked portal. To manage the behavior of this portal variant, an *InteractiveDoor* script was added to its parent object.

The Interactive Door may be in one of three states: **1. Closed** - the state before interaction begins, in which the door's transparency is dynamic - **2. Open** - the state after the user initiates the transition by opening the door - and **3. Following** - the state in which the portal is when the door of its linked portal is opened.

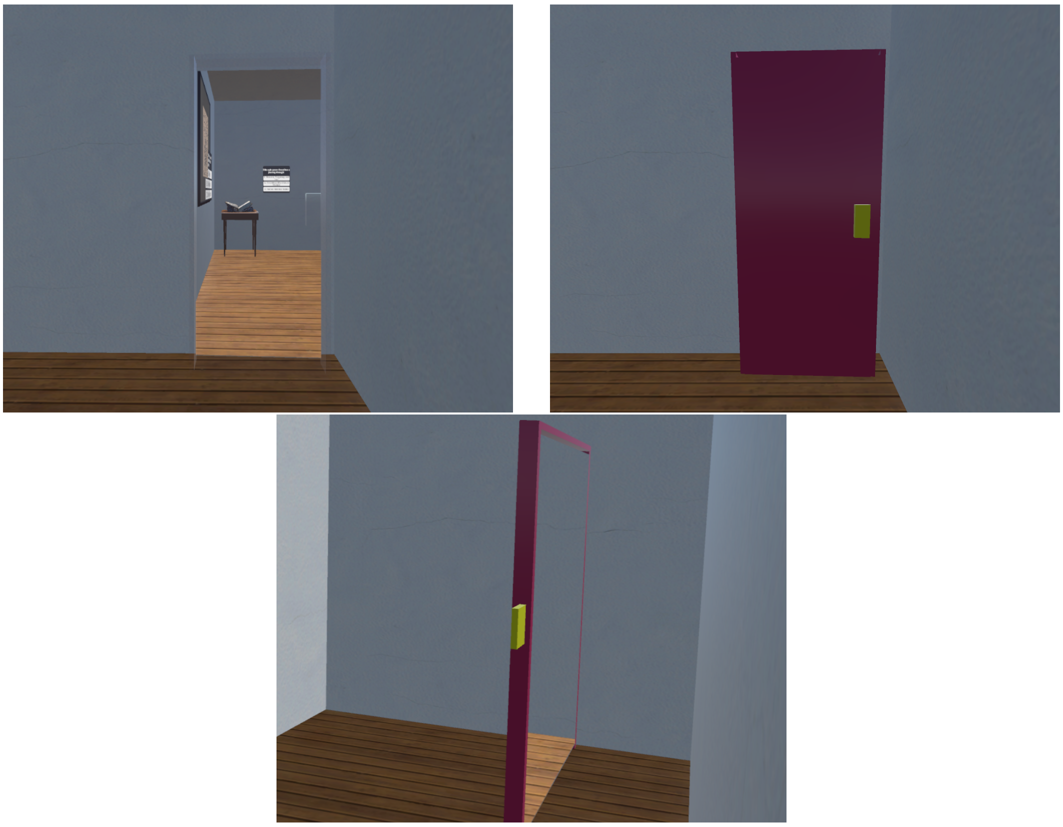

Figure 4.8: The interaction sequence for the Interactive Door: (a) From a distance, the door is transparent, providing a clear preview to aid spatial awareness. (b) As the user approaches, it becomes opaque, suggesting the need for direct interaction. (c) The user opens the door by grabbing the handle and swinging it while the portal accompanies it, creating the necessary clearance for the user to move safely into the next space.

As described in Section 3.5.3, the Interactive Door is designed to allow users to perceive the connected room through a continuous preview of the portal behind door, with the door's transparency dynamically changing based on the proximity of the user. Hence, when 'Closed', the portal on the Interactive Door has a reversed preview and the transparency of the door changes dynamically according the position of the Head of the user. The *InteractiveDoor* script receives a minimum distance, d_{min}, and a maximum distance, d_{max}, to calculate the α value of the transparency of the door's material using the following function:

$$\alpha(d) = \begin{cases} 1 & d \leq d_{\text{min}} \\ \dfrac{d - d_{\text{min}}}{d_{\text{max}} - d_{\text{min}}} & d_{\text{min}} < d < d_{\text{max}} \\ 0 & d \geq d_{\text{max}} \end{cases}$$

where:

- $\alpha(d)$ is the transparency (alpha value, ranging from 0 to 1),

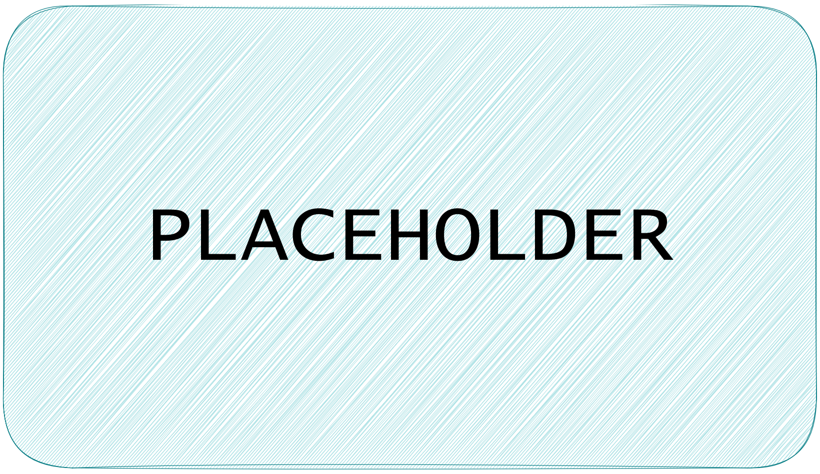

Figure 4.9: Interactive Door components.

- d is the distance between the user's head and the door,
- d_{min} is the minimum distance (fully opaque for $d \leq d_{\text{min}}$),
- d_{max} is the maximum distance (fully transparent for $d \geq d_{\text{max}}$).

When a user uses their virtual hands to grab the handle, the interacted door transitions to the 'Open' state. In the 'Open' state the door that has been opened by the user moves according to the pulling force the user does while still doing the grab/pinch gesture with the virtual hand. With a complementary hinge joint component within the hierarchy of the Interactive Door, the movement of the door can be calculated using the physics engine. The torque, τ, which measures how strongly a force tends to make an object rotate around a pivot, is calculated by the physics engine through the following equation:

$$\tau = F \cdot r \cdot \sin(\theta),$$

where:

- F is a force applied at the handle,
- r distance from the hinge to where the force is applied,
- θ angle between F and r.

As the door approaches the maximum angle of 90°, the physics engine applies a constraint torque to prevent further rotation, keeping the door in place if more force is applied. With the Interactive Door in an 'Open' state, the *Portal* script allows the teleportation of objects containing the *PortalTraveller* script.

As described above, when an Interactive Door transitions to the 'Open' state, its linked door automatically enters the 'Following' state. In this state, the linked door synchronizes its rotation with the 'Open' door, matching its angle throughout the opening motion. This ensures that the portals remain perfectly aligned and overlapped while the door is being opened.

4.2.4 Revolving Door

4.3 Summary

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Evaluation

In order to assess the developed system and answer the Research Questions proposed on Section 1.2, a user study was conducted. This chapter presents the design and results of this user study, exploring the findings and conclusions on the impact of the developed portal variants on usability, naturalness and spatial understanding.

add summary paragraph

5.1 Protocol

To ensure the validity of the results, the user study was always conducted in the same room, with an available tracking space of approximately 2.5m x 2.5m, providing conditions comparable to those available to most common VR users [**<empty citation>**]. In addition, the same hardware was used across all participants to ensure consistency, being composed of: an *Oculus Quest 3* Head-Mounted Display (HMD) and a computer equipped with an NVIDIA GeForce RTX 3070 graphics card, 16 GB of RAM and an Intel Core i5-9600K CPU.

Each participant experienced the four portal techniques—Traditional Portals, Movable Portals, Interactive Doors, and Revolving Doors—while performing the same tasks within the same Virtual Environment (VE). The only variation between participants was the order in which the portal techniques were presented, which followed a Latin Square design to minimize bias.

5.1.1 Procedure

add appendix

Add VRSQ annex

The experimental session commenced by asking the participant to read the informed consent presented in . After reading, agreeing and signing the consent form, users were asked to fill a pre-session Virtual Reality Sickness Questionnaire (VRSQ), available in . Finally, before starting the session, participants also filled a characterization questionnaire that collected information about age, gender, education, experience in VR and video games, and sight problems.

After filling these initial forms, the experiment started with a brief of the context and instructions needed for the study given by the researcher. The participant was instructed on how to walk around the environment, how to use their virtual hands and information

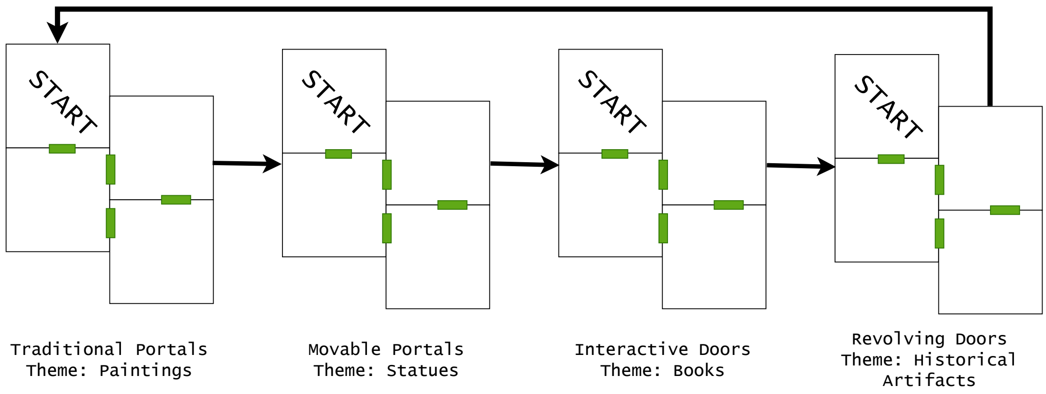

Figure 5.1: Layout of the VE of the user study.

regarding the tasks they were asked to perform. With the instructions provided, the participant started wearing the HMD and was free explore to explore the VE and complete the aforementioned tasks.

The VE depicted a museum, structured in four thematic sections, each composed of four rooms populated with exhibition items. Every exhibit included an associated quiz and curious fact, designed to encourage engagement and support spatial memory. Each section differed from the others by theme, visual appearance, and the portal technique used to connect the rooms. Additionally, the starting room of each section featured a uniquely colored floor to help participants reorient themselves when asked to return to the starting point (Figure 5.1).

Within each section, participants completed three tasks in sequence: **1.Exploration Task:** The user freely explored the rooms using the section's associated portal technique, aiming to see and respond to every exposition items' quiz. After exploring the whole section, the user was asked to return to the starting room. **2.Spatial Memory Task:** The user was then prompted to point toward an object located in a previously visited room from the starting room. To reduce memory bias, participants were allowed to revisit the object before returning to the designated location. **3.Subjective Evaluation:** Finally, the user answered two Likert-scale questions (7-point scale) assessing naturalness and ease of use. These questions were presented and answered inside the VE to avoid breaks in presence.

Throughout the session, the experimenter observed and recorded notable behaviors such as hesitations, verbal cues (e.g., "How do I..."), or repeated attempts to interact with portals, as objective indicators of usability.

After completing all four sections, participants removed the HMD and filled a post-session questionnaire. This included a post-session Virtual Reality Sickness Questionnaire (VRSQ), am Igroup Presence Questionnaire (IPQ), an Immersive Experience Questionnaire (IEQ), additional Likert-scale items assessing overall usability, a ranking of the four portal techniques by preference, open-ended questions on perceived strengths and weaknesses, and demographic data. Each session lasted approximately 30-45 minutes, depending on the participant's exploration speed.

5.1.2 Data Collection

As mentioned, several methods of quantitative and qualitative data were retrieved from this experiment throughout the procedure. For clarity, the collected data are grouped into the following categories:

Usability and Naturalness: To assess subjective user experience, participants rated their agreement with two statements on a 7-point Likert scale (1=Strongly Disagree, 7=Strongly Agree): (1) "I found the transition between rooms natural" and (2) "I found the transition between rooms intuitive / easy to use". To supplement subjective ratings, we captured an objective usability metric by logging usability hesitations. These were defined as any significant pause, verbal expression of confusion, or repeated, incorrect interaction attempts observed by the experimenter.

Spatial Understanding: This was quantified through a pointing task where participants indicated the direction of a target object in a previously visited room. The primary metric was the absolute pointing error, measured in degrees.

Presence and Immersion: The overall sense of being "in" the virtual environment was measured using two standard validated questionnaires: the Igroup Presence Questionnaire (IPQ) and the Immersive Experience Questionnaire (IEQ).

Cybersickness: To monitor for potential adverse effects, participants completed the Virtual Reality Sickness Questionnaire (VRSQ) both before (pre-exposure) and immediately after (post-exposure) the experiment.

User Preference and Qualitative Feedback: Finally, we captured overall user preference by asking participants to order the four portal techniques from 1 (most preferred) to 4 (least preferred). To understand the context behind these rankings and other ratings, the post-session questionnaire included open-ended questions prompting participants to describe the perceived strengths and weaknesses of each portal.

5.2 Tasks

5.2.1 Rooms

5.2.2 Exposition Items

5.2.3 Pointing Task

5.2.4 Usability Questionnaire

5.3 Results

The results and insights from the user study are presented in this section. After presenting the demographic data of the participants who took part in this user study, the collected data aforementioned in the previous section is presented. Finally, a discussion of the results is presented, addressing the Research Questions proposed in Section 1.2.

5.3.1 Demographics

We analyzed the data from 31 participants (19 male, 11 female, 1 non-binary), with an average age of 22.5 years (SD = 1.75, range 22-28). In terms of educational backgrounds, 64.5% of participants held a Bachelor's degree, 29% held a Master's degree and 6.5% reported having High School education or equivalent.

Regarding prior experience with VR, 3.2% of participants reported using VR frequently(weekly or more), 3.2% use VR monthly, 29% used VR a few times a year, 38.7% reported using VR once or twice and 25.8% had never used VR before.

In terms of playing video-games, 22.6% of participants reported playing games frequently(daily), 16.1% play them weekly, 35.5% play them monthly, 19.4% reported playing them a few times a year and 6.5% don't play video-games.

When asked to rate their perceived sense of orientation/direction on a scale of 1 to 5, 35.5% of participants rated themselves as 4 and another 35.5% as 3, so most answers clustered on these values. Following this, 12.9% of participants rated themselves as 5, another 12.9% as 2 and 3,2% as 1.

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5.3.2 Spatial Understanding

At the end of each section, users were tasked to point in their perceived direction of a target object in a previously visited room, in order to assess users' spatial perception. The primary metric was the absolute pointing error between the answer provided by the participant and the preview-based position of the target object, measured in degrees.

A Shapiro-Wilk test showed the data were not normally distributed ($p < .05$), thus justifying the use of the non-parametric Friedman test. Our analysis revealed a highly significant difference in pointing error across the four portal conditions, $\chi^2(3, N{=}31) = 28.39$, $p < .001$. The distributions of these errors are visualized in Figure 5.2. The Revolving

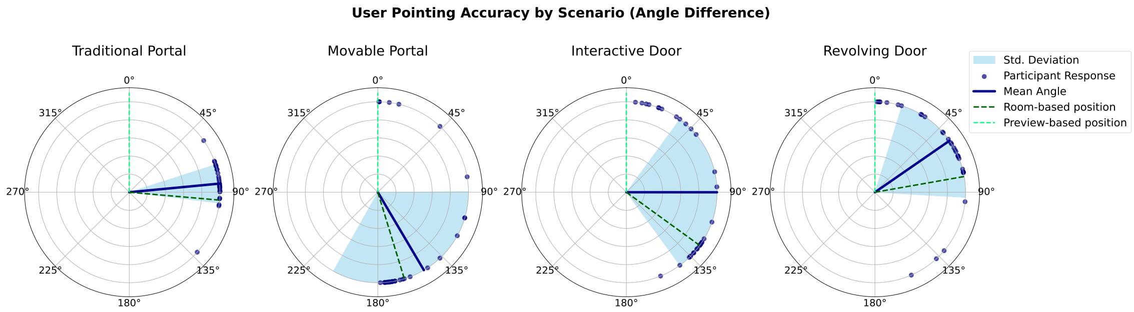

Figure 5.2: Polar plots showing the distribution of angular error in the pointing task by portal condition.

Door portal was associated with the lowest median pointing error (Mdn = 60.66°). The Traditional portal followed with a moderate error (Mdn = 85.62°), and the Interactive Door showed a higher error (Mdn = 120.96°). The Movable Portal produced the highest pointing error by a large margin (Mdn = 165.87°).

5.3.3 Usability and Naturalness

To assess subjective user experience, at the end of each section, participants rated their agreement with two statements on a 7-point Likert scale (1=Strongly Disagree, 7=Strongly Agree): (1) "I found the transition between rooms natural" and (2) "I found the transition between rooms intuitive / easy to use".

This data was analysed using a non-parametric Friedman test. Significant results were followed by post-hoc Wilcoxon signed-rank tests with a Bonferroni correction applied, resulting in a significance level of $p < .0083$.

Naturalness: The user ratings for perceived naturalness are visualized in Figure 5.3. A Friedman test revealed a highly significant difference in perceived naturalness across the four portal types, $\chi^2(3, N{=}31) = 27.18$, $p < .001$. Post-hoc analysis showed that the Traditional Portal (M=5.61, SD=1.15) was rated as significantly more natural than both the Movable Portal (M=3.81, SD=1.66; $p < .001$) and the Revolving Door Portal (M=4.35, SD=1.45; $p < .001$). Additionally, the Interactive Door Portal (M=5.13, SD=1.38) was rated as significantly more natural than the Movable Portal ($p = .0002$).

Ease of Use / Intuitiveness: We found a highly significant effect of the portal type on perceived ease of use, $\chi^2(3, N{=}31) = 40.60$, $p < .001$, with results shown in Figure 5.4. Post-hoc tests revealed a clear hierarchy of usability. The Traditional Portal (M=6.13, SD=1.02) was rated as significantly easier to use than all other techniques: Interactive Door (M=5.19, SD=1.74; $p = .0013$), Revolving Door (M=4.03, SD=1.56; $p < .001$), and Movable Portal (M=3.84, SD=1.44; $p < .001$). Furthermore, the Interactive Door Portal was also rated as significantly easier to use than both the Revolving Door ($p = .0054$) and the Movable Portal ($p = .0011$). No significant difference was found between the Movable and Revolving Door portals, placing them together in the lowest tier for ease of use.

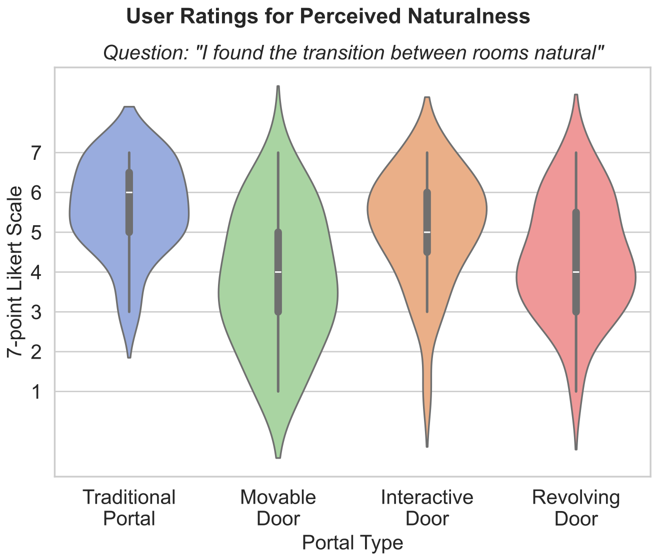

Figure 5.3: User ratings for Perceived Naturalness.

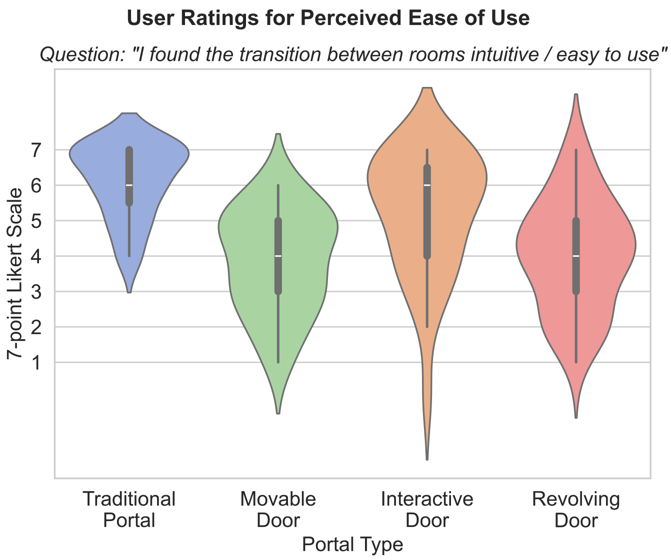

Figure 5.4: User ratings for Perceived Ease-of-Use.

To complement the subjective ratings, we analysed objective usability issues recorded by the experimenter. The number of spoken hesitations (e.g., verbal expressions of confusion) and action-based tries (*e.g.*, incorrect or repeated attempts to use a portal) for each participant were quantified.

A Friedman test confirmed that the differences between portal types were highly significant for both spoken hesitations ($\chi^2(3, N{=}31) = 23.09$, $p < .001$) and action-based tries ($\chi^2(3, N{=}31) = 71.12$, $p < .001$). As in Figure 5.5, the Revolving Door and Movable Portal generated a substantial number of usability issues. The Revolving Door, while producing a moderate number of spoken hesitations (M = 2.03), was associated with a higher mean of action-based tries (M = 13.48). The Movable Portal also proved challenging,

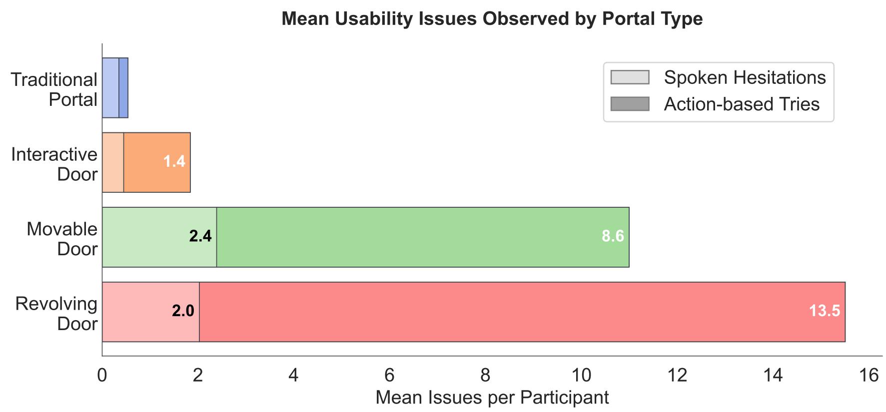

Figure 5.5: Mean number of usability issues per participant by portal type. The stacked horizontal bars show spoken hesitations (light tone) and action-based tries (bright tone) for each portal type.

resulting in the highest mean for spoken hesitations (M = 2.39) and a high number of action-based tries (M = 8.61). In contrast, the Interactive Door (Hesitations: M = 0.45, Tries: M = 1.39) and especially the Traditional Portal (Hesitations: M = 0.35, Tries: M = 0.19) were associated with negligible usability problems.

5.3.4 User Preference

To assess overall preferences, participants ranked the four portal techniques on a scale from 1 (most preferred) to 4 (least preferred) on the post-session questionnaire. An initial Friedman test, $\chi^2(3, N{=}30){=}\ 70.67$, $p{<}0.001$, shows a statistically significant difference in user preference between the four locomotion techniques, indicating that participants did not rank all techniques equally. Figure 5.6 shows the results of the preference rankings. Traditional Portals scored the highest, followed by the Interactive Doors, then Revolving Doors, with Movable Portals being ranked the lowest.

Adjacent comparisons were conducted within each rank based on technique frequency, with only one reaching statistical significance: at the 4th rank, Revolving Doors were significantly more likely to be rated least preferred compared to Interactive Doors (p = 0.0153 after Bonferroni correction). Although participants showed a clear preference towards Traditional Portals, this preference missed statistical significance when compared to the Interactive Doors(p = 0.0169 vs adjusted α = 0.0167), the second most top-ranked technique.

5.3.5 Presence

As previously mentioned, presence was measured using the Igroup Presence Questionnaire (IPQ). Overall, participants reported moderate to high scores across subscales (Spatial Presence: M = 5.5, SD = 0.45; Involvement: M = 4.42, SD = 0.4; Experienced

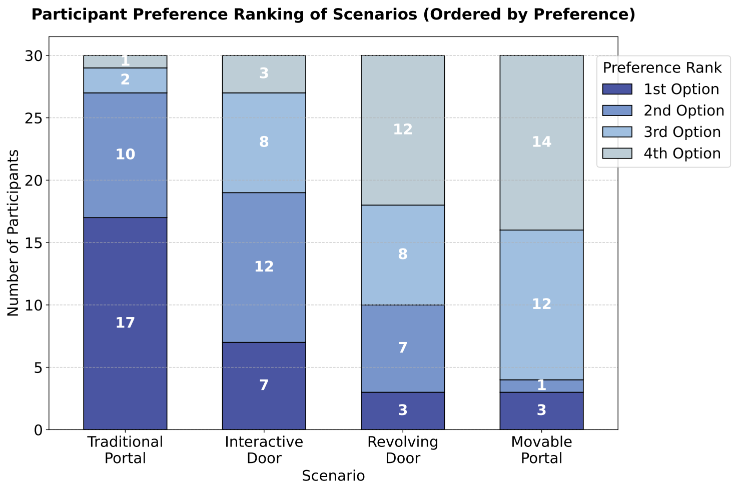

Figure 5.6: Participant preference rankings for the four interaction scenarios.

Realism: M = 4.58, SD = 0.78), indicating a moderate to high sense of presence during the VR experience.

5.3.6 Cybersickness

Cybersickness was assessed using the Virtual Reality Sickness Questionnaire (VRSQ). Participants reported low levels of symptoms both before (M = 2.23, SD = 3.13) and after the session (M = 2.68, SD = 3.91), suggesting that the experience had minimal impact on cybersickness.

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5.3.7 Qualitative Feedback

Participants explained their preferences for the different portal types through open-ended questions in the post-session questionnaire. We also collected voluntary oral commentary provided throughout the session.

During the Traditional Portal section, participants expressed some dissatisfaction with having to walk around the portals to preview the next room before entering. Concerns were also raised about getting lost or forgetting which rooms they had already visited. Despite these issues, most participants justified their preference for Traditional Portals by describing them as "the easiest to use" and "most natural". Several participants noted that this technique provided the closest experience to a real museum, as "in a real museum, you only have to pass through a doorway to move to the next room".

Regarding the Movable Portal, some participants reported feelings of confusion (e.g., "What am I supposed to do?", "Did I do that?") or discomfort (e.g., "This feels weird.", "Don’t spin!"(speaking to the portal)), while others expressed amusement and enjoyment (e.g., "This is fun!", "I can move it? How cool!"). Participants that preferred this technique overall appreciated the sense of control from being able to move the portal. The steep learning curve and higher effort required were frequently cited drawbacks.

Participants reacted positively to the Interactive Door upon first contact (e.g., "This one is cool!", "Ah, wow!"). Questionnaire responses highlighted that the door's opening mechanism felt intuitive and immersive, which participants often attributed to its resemblance to real-world door interaction, requiring minimal cognitive effort. A few participants did report some initial confusion regarding the portal's movement, noting that it follows the door as it is opened.

Initial interactions with the Revolving Door were challenging, with participants asking questions such as "Am I supposed to pull it or push it?" and "I was seeing where I was going... but now I don't?" or expressing general confusion (e.g., "This is weird."). However, by the end of the session, participants reported greater comfort with the technique (e.g., "After understanding it, it was easy."). While the steep learning curve was frequently mentioned as a drawback in the questionnaire, several participants who preferred the Revolving Door highlighted its fun and immersive qualities.

5.4 Discussion

The main goal of the presented work was to evaluate four VR locomotion techniques based on natural walking with portals, focusing on their impact on usability, spatial understanding, and user preference. The findings from the study with 31 participants provided insights into these aspects of UX, allowing the purpose of this study to be addressed by tackling the research questions defined in Section 1.2.

In this section, the research questions are addressed through the presentation and discussion of the insights gained from the user study.

Q1 - What are the effects of a dynamic preview in regard to users' sense of space?

The pointing task, performed at the end of every section of the virtual museum, was designed to address this issue, by providing a better insight into how the participants perceived space. The results reveal nuanced differences in how each portal design affects the perception users have of the layout of the VE, but highlights a big difference between Traditional Portals and the other variant portal designs.

The results of the pointing task in the Traditional Portal section present the lowest variation in angular error, with most responses clustering around a median of 85.62°. This angle closely corresponds to the position of the object in the overlapping architecture. In contrast, responses for the other techniques were more widely dispersed, as answers no longer clustered on the same position. Several participants utilized the preview capabilities of the portal variants when prompted to point towards the object, pointing at the object through the portal's preview.

The clear distinction between the results of the portal variants' sections and the Traditional Portal's section suggests that participants relied on the preview features to inform their spatial judgments, indicating that dynamic previews can influence and potentially enhance the sense of spatial continuity.

Q2 - What elements of UX do users prioritize when interacting with these navigation techniques?

The results of the study suggest that participants primarily prioritized ease of use and naturalness when interacting with the different portal designs. The preference rankings reveal that a majority of participants preferred to use the Traditional Portals and the Interactive Portals, followed by the Revolving Door and the Movable Portal.

Traditional Portals were consistently rated as the most intuitive and easiest to use, which corresponds with the low amount of usability issues registered when using this portal and the commentary provided by the participants. Interactive Doors were also perceived positively, as their mechanics closely mimicked real-world door interactions, making the transition feel natural and intuitive, also backed by the low number of usability issues and participant commentary. In contrast, Movable Portals and Revolving Doors, while appreciated by some participants for the added sense of control or the stronger perception of continuous space they provided, were generally hindered by steeper learning curves and higher cognitive demands.

Taken together, these findings indicate that users tend to value straightforward, familiar, and low-effort interactions above more complex mechanics that may enhance spatial continuity but reduce immediate usability.

Q3 - What are the strong points for each of these techniques, in regard to VE navigation?

Through the commentary and experience observed in this study, it was possible to conclude that each portal technique presented distinct strengths for VE navigation.

Traditional Portals stood out for their simplicity and reliability, being mostly praised for their ease of use and efficiency. Movable Portals offered participants a sense of control over their navigation, enabling them to reposition the portal and adjust how space was experienced, which some users found engaging and empowering despite the higher effort required. Interactive Doors were valued for their intuitive and immersive interaction, as the door-opening mechanic resembled a familiar real-world action and contributed to a natural sense of transition between rooms. Revolving Doors, while initially less intuitive, were highlighted for providing the smoothest feeling of spatial continuity, with their guided redirection enhancing the perception of flow across rooms once participants became accustomed to the technique.

5.5 Summary

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6

Conclusion

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