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Bachelor in Computer Science

VR LAB: USER INTERACTION IN VIRTUAL ENVIRONMENTS USING SPACE AND TIME MORPHING

MASTER IN COMPUTER SCIENCE

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“Perhaps only in a world of the blind will things be what they truly are.” (José Saramago)

Abstract

Virtual Reality (VR) allows exploring changes in space and time that would otherwise be difficult to simulate in the real world. It becomes possible to transform the virtual world by increasing or diminishing distances or playing with time delays. Analysing the adaptability of users to different space-time conditions allows studying human perception and finding the right combination of interaction paradigms.

Different methods have been proposed in the literature to offer users intuitive techniques for navigating wide virtual spaces, even if restricted to small physical play areas. Other studies investigate latency tolerance, suggesting humans' inability to detect slight discrepancies between visual and proprioceptive sensory information. These studies contribute valuable insights for designing immersive virtual experiences and interaction techniques suitable for each task.

This dissertation presents the design, implementation, and evaluation of a tangible VR Lab where spatiotemporal morphing scenarios can be studied. As a case study, we restricted the scope of the research to three spatial morphing scenarios and one temporal morphing scenario. The spatial morphing scenarios compared Euclidean and hyperbolic geometries, studied size discordance between physical and virtual objects, and the representation of hands in VR. The temporal morphing scenario investigated from what visual delay the task performance is affected. The users' adaptability to the different spatiotemporal conditions was assessed based on task completion time, questionnaires, and observed behaviours.

The results revealed significant differences between Euclidean and hyperbolic spaces. They also showed a preference for handling virtual and physical objects with concordant sizes, without any virtual representation of the hands. Although task performance was affected from 200 ms onwards, participants considered the ease of the task to be affected only from 500 ms visual delay onwards.

Keywords: Virtual Reality, Time Perception, Space Perception, Human-Computer Interaction, Tangible User Interface

Resumo

A Realidade Virtual (RV) permite explorar mudanças no espaço e no tempo que de outra forma seriam difíceis de simular no mundo real. Torna-se possível transformar o mundo virtual aumentando ou diminuindo as distâncias ou manipulando os atrasos no tempo. A análise da adaptabilidade dos utilizadores a diferentes condições espaço-temporais permite estudar a perceção humana e encontrar a combinação certa de paradigmas de interação.

Diferentes métodos têm sido propostos na literatura para oferecer aos utilizadores técnicas intuitivas de navegação em espaços virtuais amplos, mesmo que restritos a pequenas áreas físicas de jogo. Outros estudos investigam a tolerância à latência, sugerindo a incapacidade do ser humano de detetar ligeiras discrepâncias entre a informação sensorial visual e propriocetiva. Estes estudos contribuem com valiosas informações para conceber experiências virtuais imersivas e técnicas de interação adequadas a cada tarefa.

Esta dissertação apresenta o desenho, implementação e avaliação de um Laboratório de RV tangível onde podem ser estudados cenários de distorção espaço-temporal. Como estudo de caso, restringimos o âmbito da investigação a três cenários de distorção espacial e um cenário de distorção temporal. Os cenários de distorção espacial compararam geometrias Euclidianas e hiperbólicas, estudaram a discordância de tamanho entre objetos físicos e virtuais, e a representação das mãos em RV. O cenário de distorção temporal investigou a partir de que atraso visual o desempenho da tarefa é afetado. A adaptabilidade dos utilizadores às diferentes condições espaço-temporais foi avaliada com base no tempo de conclusão da tarefa, questionários, e comportamentos observados.

Os resultados revelaram diferenças significativas entre os espaços Euclidiano e hiperbólico. Também mostraram a preferência pelo manuseamento de objetos virtuais e físicos com tamanhos concordantes, sem qualquer representação virtual das mãos. Embora o desempenho da tarefa tenha sido afetado a partir dos 200 ms, os participantes consideraram que a facilidade da tarefa só foi afetada a partir dos 500 ms de atraso visual.

Palavras-chave: Realidade Virtual, Perceção do Tempo, Perceção do Espaço, Interação Pessoa-Máquina, Interface de Utilizador Tangível

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Acronyms

3D Three-Dimensional 7

AR Augmented Reality 4, 31, 45

CPU Central Processing Unit 2

FOV Field of View 9

HCI Human-Computer Interaction 2, 7, 8

HMD Head-Mounted Display 1, 79

IPQ Igroup Presence Questionnaire 61

NFT Natural Feature Tracking 46

OTApp Object Tracking Application 38, 43, 57

PC Personal Computer 38

RV Realidade Virtual vii

SIFT Scale Invariant Feature Transform 46

SSQ Simulator Sickness Questionnaire 61

UI User Interface 30

UX User Experience 8

VE Virtual Environment 7

VEs Virtual Environments 1, 7, 79
VR Virtual Reality vi, 1, 7, 79
VRApp VR Application 38, 39, 57

1 Introduction

Virtual Reality (VR) tools allow creating safe Virtual Environments (VEs) to simulate scenery identical or with sparse similarities to reality. Immersive interfaces offer powerful tools for visualization and interaction design, transforming the sense of space and time.

The stimuli in a VR experience are primarily visual, displayed by the Head-Mounted Display (HMD). However, the experience is all the more immersive, the more human senses it triggers. User studies in VR help understand human perception and which techniques are best suited for each type of experience. For rooms with limited space, the user can navigate through the vast virtual space using teleportation techniques or portals [1, 2]. In sports or military training scenarios, a more realistic training experience is expected where the user is able to walk freely through the virtual world. Real walking in VR typically relies on redirection techniques [1–5] that lead the user through the virtual space without colliding with obstacles in the physical play area. These techniques rely on the human inability to detect minor discrepancies between visual information and proprioception (i.e., the sense of self-movement and body position). Movements can also be warped in scenarios that require haptic feedback for more precise movements, such as surgical training [6]. Supporting tangible objects and representing the user's body (e.g., hands) can increase the sense of presence, body ownership, and performance [7–10].

Designing and developing enjoyable VR experiences requires choosing interaction techniques that fit the system requirements, establishing tolerable latency, and enhancing immersion through realistic stimuli. VR makes it possible to simulate different conditions of space and time and analyse whether these prove intuitive for users.

1.1 Motivation

Due to human visual dominance, small offsets introduced by redirection techniques lead users to adapt their movement unconsciously, taking advantage of humans' inability to detect slight discrepancies between visual and proprioceptive sensory information [11].

Redirection techniques have been proposed to overcome tracking space limitations, making it possible to create infinite virtual worlds. Teleportation [1], portals, saccadic redirection [4], non-Euclidean geometry [12], redirected touching, and haptic retargeting [13, 14] are examples of methods that manipulate the user's perceived self-motion to create an illusion of larger virtual spaces. Research on depth and size perception in VR has suggested that depth and size are usually underestimated [15]. Furthermore, comparing the size of visual objects to haptic objects also showed a dominant functional priority of visual size perception [16]. The results of all these user studies provide important implications for the design of 3D visuo-haptic Human-Computer Interaction (HCI).

On the topic of time, we immediately think of the adverse effects that latency can have in high-precision tasks, remote communication, or collaborative environments [17–20]. Latency is a crucial design parameter for any VR system since the processing of video signals to generate the visual HMD scene is very CPU-consuming. Although there are solutions for building low latency systems [21], it is essential to establish a delay interval beyond which the task becomes unfeasible for users. Beyond latency issues, time can be manipulated in ways that prove to be useful, such as playback or cancelling actions. For example, when a baseball player hits the ball in a sports training context, it is not always necessary to see the whole trajectory to understand if the ball will hit the desired spot. It may be interesting to speed up or even cancel the action to save time. Playback review can also help players improve their technique [22].

Studies on latency and spatial distortion techniques have sought to establish values up to which spatiotemporal changes users cannot detect [13, 17, 23], or analyse whether new approaches are intuitive for users. To increase the knowledge in these fields, our research proposes creating a tangible VE as a study site to explore the users' adaptability to different space and time conditions.

1.2 Research Questions

In a VR context, space and time can be manipulated in a variety of ways. To narrow the scope of this research, we defined three spatial morphing scenarios and one temporal morphing scenario. The user studies were primarily aimed at studying the adaptability of users to different scenarios based on performance and subjective ease. Performance refers to the time it takes the user to complete the task, and subjective ease intends to identify whether the user found the task easy.

The two main research questions were as follows:

- **Q1** - Is there a significant difference in performance and subjective ease between performing tasks in a Euclidean space versus hyperbolic space?
- **Q2** - After which delay value is there a significant difference in performance and subjective ease of the task?

Hyperbolic geometry, a non-Euclidean geometry, rejects the parallel postulate that stated that through a point not on a given line, there is exactly one line parallel to the given line. In hyperbolic geometry, through a point not on a given line, there are at least two lines parallel to the given line. This property makes it possible to access much more area within a given distance. While the geometric benefits of hyperbolic space have already been shown in unusual virtual worlds [24, 25], the applicability of these benefits has been very little experienced in common tasks in a VR context. Initial user testing by Pisani et al. [12] suggests that people can walk in hyperbolic VEs without significant disorientation and may branch structures more intuitively than in Euclidean space. To further explore the applicability of hyperbolic spaces in VR, question **Q1** aims to analyse whether people can move tangible objects in hyperbolic spaces as comfortably as in Euclidean spaces.

Studies related to visual and/or haptic delay have presented different results on how the latency of visual feedback has a strong influence on haptic task performance [17, 26–31]. With question **Q2**, we intend to present our results showing from which delay values performance and subjective ease are significantly affected.

The secondary questions are:

- **Q3** - In a tangible VR context, can the difference between the size of the physical object and its virtual representation affect task performance?
- **Q4** - In a tangible VR context, does the hand representation help the user perform the proposed tasks?

Controller-free hand-tracking technology allows users to interact with tangible objects using their bare hands, increasing the intuitiveness and naturalness of interaction. Question **Q3** aims to analyse if there is a difference in performance when the virtual and physical objects have different sizes. In turn, question **Q4** intends to study if hand representation in the VE helps the user perform the tasks or if, conversely, hands can be omitted since the user perceives the objects through touch. The answers to these questions can contribute to guidelines for designing tangible VR systems that are intuitive for users.

1.3 Objectives

Considering the formerly established research questions, the following objectives were defined to conduct the research work.

1 **Design and implement a tangible VR Lab;**
Develop an immersive VR scene using Unity 3D and its XR Toolkit. Establish the connection between tangible objects and the VR scene through Vuforia SDK and Mirror Networking API.

2 **Design and implement space and time morphing scenarios;**
Create simple games that incorporate the spatiotemporal conditions under study and integrate them into the tangible VR Lab.

3 **Conduct user studies and analyse the acquired results.**
Design and conduct user studies to gather results regarding user performance, subjective ease and preference to the morphing scenarios under research. Analyse the acquired results to answer the research questions.

1.4 Solution Overview

Following the stipulated objectives, the work developed throughout this dissertation can be divided into three major stages: development of the tangible VE, incorporation of the different spatiotemporal morphing scenarios and user tests.

In the first stage, a VR scene (Figure 1.1) was designed to immerse the user in a comfortable and wide space. Later, this virtual world was empowered to support passive haptic feedback, enabling the users to handle the virtual objects with their bare hands. The object tracking mechanism was implemented based on a marker-based system (commonly used in Augmented Reality (AR) applications), particularly designed to facilitate the future addition of multiple physical objects of various shapes and sizes.

The morphing scenarios designed explored three space morphing scenarios (*Spatial Function Scenario*, *Object Size Scenario*, *Hand Model Scenario*) and a single time morphing scenario. In the *Spatial Function Scenario*, four mathematical functions (two linear and two hyperbolic) were implemented to determine the mapping of tangible objects in the virtual world, giving them different behaviours. In the *Object Size Scenario*, the scale of the virtual objects was manipulated to study three different sizes (small, normal, large). The *Hand Model Scenario* used a hand tracking engine to represent the hands through a realistic and abstract hand model. The *Time Morphing Scenario* explored different levels of visual delay applied to the object movement to study how the delay could affect performance and task ease.

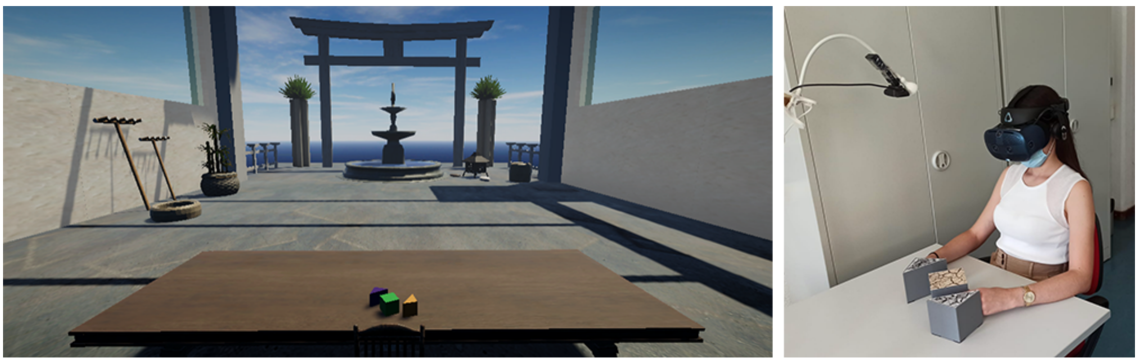


Figure 1.1: VR Lab - a tangible virtual environment where user studies can be conducted to explore different conditions of space and time.

Finally, to study the user behaviour to the different space and time conditions, a user study was designed and conducted to collect data on performance, subjective ease and user preference. Subsequently, these data were statistically analysed to draw conclusions and formulate the answers to the research questions stipulated in a first instance.

1.5 Contributions

The main contributions that can be drawn from the work developed throughout this dissertation are the following:

- **Tangible VR approach**: the developed solution consists of a marker-based method that only requires a webcam to integrate multiple and diverse tangible objects into a VR experience;
- **VR Lab**: the VR Lab developed can be an experimental site for conducting user studies to explore the suitability of different space and time conditions. Although it is a prototype, it can be configured to change or add new morphing scenarios;
- **Use case scenarios**: the design and implementation of four morphing scenarios and two games with tangible interaction support;
- **User study results**: User testing results validate the overall efficiency of the system. Besides, the research conducted was based on related work in the field of HCI in VR. Our results enrich the literature and offer insights that can help designers implement interactive 3D applications that meet users' needs and preferences.

The four morphing scenarios were chosen after reviewing related work in the area of HCI in VR. Starting from hypotheses still little explored or with divergent results in the literature, we conducted psychomotor studies using virtual elements in a common virtual space. We believe that the concept of our work will leverage the study of other scenarios that, like the chosen ones, are relevant to better understand human spatial and temporal perception in VR.

1.6 Document Structure

This first chapter introduced the context of the work developed throughout the dissertation, presenting some challenges in creating VEs with intuitive interactions suitable to each VR experience and the users' preferences. The research questions were defined to guide the investigation on users' adaptability under different conditions of space and time while interacting with tangible objects.

Chapter 2 presents state of the art, starting with a brief introduction on HCI concepts in VEs, followed by works related to the perception of space and time in VR. The topic regarding space in VR presents techniques to navigate and interact with objects in the virtual world. Regarding time in VR, a survey is presented about latency tolerable by users in tangible VEs.

Chapter 3 starts by substantiating the research questions defined based on the literary review elaborated in the previous chapter. Next, the system requirements and design decisions are described, followed by the case study chosen to address the different spatiotemporal morphing conditions.

Chapter 4 elaborates on the system development, starting by listing the main technological tools used in the implementation process. The VR application and the tangible object tracking application are presented, as well as the network connection that links both. The implementation of the four morphing scenarios is presented individually.

Chapter 5 covers the testing phase, presenting the protocol and procedure adopted in the user study. Afterwards, an overview of the gathered data is presented, which is then analysed to draw conclusions about the system and the user performance, subjective ease and preference on the tasks performed.

Chapter 6 formulates the conclusions that can be drawn from the work carried out as well as improvements and future investigations that may arise from this dissertation.

2

State of the Art

This chapter starts by presenting theoretical concepts related to Human-Computer Interaction (HCI) in VR, followed by the two major topics of this dissertation: space and time.

A review is made on related works that study human spatial and temporal perception and interaction in Virtual Environments (VEs), whose results contribute with insights for designing more engaging and intuitive applications for users.

2.1 Virtual Environments

In the real world, our behaviour is limited by the laws of physics. The way we walk, move, and interact with people and objects are shaped by the surrounding reality restrictions. In contrast, in virtual worlds it is possible to recreate imaginary scenery with sparse similarities to reality, overcoming real-time and space limitations.

A Virtual Environment (VE) is a digital space in which the user's movements are tracked and their surroundings rendered and displayed to the senses, according to the user's actions [32]. Although VEs can simulate real-world properties, virtuality is typically used to create an unreal world where the physical laws governing gravity, time, and material properties no longer hold [33].

The design of VEs is possible through the scientific and technical domain that uses computer science and behavioural interfaces: Virtual Reality (VR). VR allows simulating the behaviour of Three-Dimensional (3D) entities, which interact in real-time with each other and with one or more users in pseudo-natural immersion via sensorimotor channels [34]. VR brings participants out of the physical reality to virtually change time, place, and the type of interaction. Witmer and Singer [35] were among the first to describe these senses of immersion and presence, which are two core concepts in VR. **Immersion** is the psychological experience of losing oneself in the digital environment and shutting out cues from the physical world. **Presence** is the subjective experience of being in one place or environment, even when physically situated in another.

The challenges of VR include designing environments that lead users to be completely distracted from the real world and understanding which parameters improve the User Experience (UX) and how it is possible to measure them.

2.1.1 HCI in VEs

Human-Computer Interaction (HCI) is a multidisciplinary field of study focusing on the design, implementation, and evaluation of interactive computer-based systems [36], in particular, the interaction between humans and computers. When confronted with a product or system, the user forms a momentary impression, which evolves over time. This process produces emotional responses before, during, and after the product's use, which largely determines whether the experience will be considered positive or negative.

In a VR application, users are immersed in and interacting with a world where they perceive, decide, and act. For the User Experience (UX) to be satisfactory, it is necessary to analyse, model, and create interfaces for user immersion and intuitive interaction in VEs [34]. There are commonly two ways to measure UX in immersive VEs, either by objective methods or subjective methods [37]. **Subjective methods** provide results from the user's perspective and are often used to understand the user's subjective opinions and attitudes. Interviews and questionnaires are examples of subjective methods. **Objective methods** provide results through experimental evidence. For example, measuring **cybersickness** (i.e. the cluster of discomfort symptoms experienced in a VE) based on an objective approach analyses postural disturbances or physiological signs rather than a motion sickness questionnaire. It is expected that the combination of both subjective and objective methods might provide more reliable results.

Table 2.1: Common methods to measure perception, presence, attention, and motion sickness (adapted from Merino et al. [38]).

Aspect	Acronym	Method Description	Approach
Perception	2-AFC	Two-Alternative Forced-Choice method	Objective
	2-IFC	Two-Interval Forced-Choice method	Objective
	ACR11-HR	Absolute Category Rating	Subjective
	SAQI	Spatial Audio Quality Inventory	Subjective
Presence	AD1	Ad-hoc Post Experimental Questionnaire	Subjective
	AD2	Ad-hoc Co-Presence Questionnaire	Subjective
	BRQ	Body Representation Questionnaire (Embodiment)	Subjective
	IOS	Inclusion of Other in the Self Scale	Subjective
	IPQ	The Igroup Presence questionnaire	Subjective
	MEC	Spatial Presence Questionnaire	Subjective
	SPQ	Social Presence Questionnaire	Subjective
	MTQ	McKnight Trust Questionnaire (Trust)	Subjective
	TPI	The Temple Presence Inventory	Subjective
Attention	2-AFC	Two-Alternative Forced-Choice method	Subjective
	AD4	Ad-hoc Self-Report Questionnaire	Subjective
	VisEng.	User Engagement Self-Report Questionnaire	Subjective
	ET	Eye-tracking	Objective
	HT	Head-tracking	Objective
Motion sickness	SSQ	Simulator Sickness Questionnaire (Fatigue)	Subjective

Merino et al. [38] presented a systematic review with standard evaluation methods for evaluations in VEs. Table 2.1 shows some of the most commonly used methods to measure perception, presence, attention, and motion sickness. Most methods are subjective, and the vast majority are questionnaires. Objective methods include tracking eye movements or head movements.

Questionnaires are among the most common research tools in VR evaluations and user studies. However, transitioning from the virtual world to the physical world to fill out the questionnaires can lead to systematic biases due to breaks in presence. On the other hand, if the questionnaires are answered at the end, the user may feel fatigued or have forgotten about the first minutes of the experience. Studies on this topic [39, 40] suggested that breaks in presence might be minimized if questionnaires are answered in the VE where the experience takes place.

2.1.2 Immersion

UX in VR is enhanced with three essential technologies - 3D stereoscopic display, wide field of view display, and low latency head UX in VR is enhanced with three essential technologies - 3D stereoscopic display, wide field of view display, and low latency head tracking. These requirements combined provide an immersive experience.

Stereoscopy is a technique for creating the illusion of depth by duplicating an image side by side to match natural eye separation and difference in perspective. This technique is the basis of HMDs functioning, allowing virtual objects to appear tangible.

The hardware **Field of View (FOV)** is a maximum visual angle of a display device [41]. On average, HMDs can support up to 110° of FOV while the human eye has both vertical and horizontal FOV of approximately 180° by 180°. The FOV may be closely related to VR sickness, which typically results from **visual-vestibular conflict**, produced when visual and self-motion senses are not concordant. Reducing the FOV during locomotion has proven to be an effective strategy to minimize visual-vestibular conflict [42].

Latency can have adverse effects in VR applications, including cybersickness symptoms that compromise presence and performance [17–19]. A higher HMD refresh rate contributes to greater synchrony between movements made in the real world and visualized in the virtual world. Thus, the latency should be as low as possible to reduce visual-vestibular conflict and prevent discomfort symptoms.

Different types of VR systems are classified by the level of immersion they provide [43]. The three main types of VR systems include non-immersive, semi-immersive, and fully-immersive display devices.

- **Non-immersive**: often called desktop VR and it is based on traditional displayed screens, including smartphones, tablets, PC monitors. The average video game can be considered a non-immersive VR experience.

- **Semi-immersive**: the experience is made possible with special monoscopic (e.g., wall-sized and curved displays) and stereoscopic devices (e.g., 3D monitors, CAVEs), providing users with a partially VE to interact with. This type of VR is commonly used for educational and training purposes.

- **Fully-immersive**: HMDs give users the most realistic experience possible. VR headsets provide high-resolution content with a wide FOV. There are three types of HMDs – mobile, standalone, or stationary devices.

2.1.3 Visual Feedback

Human beings perceive the world around them mostly through sight. It is essential to display an immersive and highly responsive world through HMD to make the user feel present in a virtual world. Different types of HMDs are available to discover the range of VR experiences. Each type has different characteristics that contribute to the user immersion and presence in the VE.

Tethered VR headsets

This type of HMD requires a constant connection to a powerful computer where all the processing is performed. Some of these headsets have built-in cameras and sensors (e.g., HTC Vive Cosmos, Oculus Quest 2) capable of tracking the user's position in the play area. Other headsets, such as the HTC Vive, requires external tracking devices placed at strategic spots for accurate tracking. Figure 2.1 illustrates the HTC Vive setup required for a room play area. Each external Lighthouse module contains Infrared Light-Emitting Diode (IR LEDs) and a laser array that sweeps in horizontal and vertical directions. The infrared sensors on the headset and controllers detect these sweeps and use the timings to determine position. Tethered headsets are currently more immersive than other HMD types due to high tracking accuracy and graphics quality. In turn, the setup requires powerful PC configurations (quality CPU, GPU, and RAM). The cable connection may also limit the user's movements.

Standalone VR headsets

Standalone HMDs, also known as wireless VR headsets, include built-in processors, sensors, battery, storage memory, and displays, discarding the need for cables or any external device to handle the processing. These devices use inside-out tracking, with cameras placed inside the HMD. These cameras calculate the user's location through position changes according to the environment and apply the same positioning to the virtual world. Without cables, users can walk more freely.

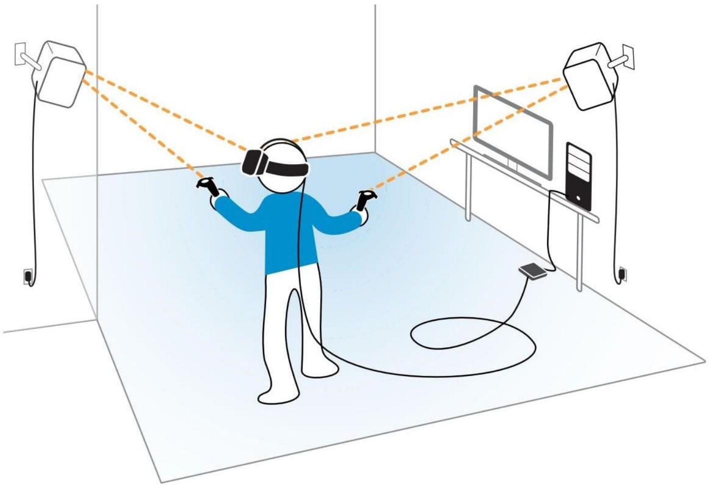


Figure 2.1: Room-scale setup through HTC Vive Lighthouse system composed by base stations (placed at the upper ends of the figure).

Smartphone VR headsets

The processing is performed in the smartphone using its built-in components and sensors. Users slide their smartphone into the headset, and the screen will be in front of their eyes, with a set of lenses that create the sense of depth. The graphical fidelity and overall interaction experience depend on smartphone capacity. Smartphone headsets offer a less immersive experience compared to the other two types presented. However, it is the most affordable and suitable alternative for sporadic uses of VR technology.

2.1.4 Haptic Feedback

The core concept of VR is the multisensory stimulation of the user, which makes it possible to feel present in a virtual experience. While HMDs and headphones enable users to perceive VEs visually and audibly, VR systems usually provide limited haptic impressions. Although the usual lightweight handheld controllers offer vibrotactile feedback, these devices cannot offer different kinesthetic impressions such as weight, resistance, or inertia.

Haptics means both force feedback (simulating object hardness, weight, and inertia) and tactile feedback (simulating surface contact geometry, smoothness, slippage, and temperature) [44]. Haptic feedback in VR context can be classified into three categories [45]:

- **Active**: Computer-controlled actuators exert forces on the user during operation, e.g., lightweight vibrotactile actuators, skin stretch mechanisms, or gloves. While providing flexible feedback, a significant limitation is the complexity, limited mobility or limited workspace.

- **Passive**: Does not require actuators since the physical props in the real environment provide tangibility to virtual objects. It is a low-complexity approach that can provide highly realistic haptic feedback.

- **Mixed**: Combine the strengths of active and passive haptics. The actuators are not used to actively render forces on the user but to transform the prop itself to change how it feels. This enables a single prop to provide different passive haptic impressions.

Besides these approaches, other techniques rely heavily on pseudo-haptics [46] that uses visual feedback to trigger haptic perception. Other concepts like redirected touching and haptic retargeting [13, 14, 47] use the visual dominance effect by warping the virtual space or the user's hand to modify how users touch tangible objects. These topics are detailed in section 2.2.

2.1.5 Tangible VR Applications

Allowing users to directly touch the objects they see through the HMD increases the sense of presence and the illusion of **embodiment** – i.e. the user has the perception of owning the avatar's body, as studied with the Rubber Hand Illusion paradigm [7]. In this experiment, after the participant spends a few minutes watching a fake hand receiving stimuli, he/she begins to perceive the rubber hand as his/her own.

Controller-free technology can increase the intuitiveness of interaction; however, higher naturalness does not always entail higher performance or usability. Masurovsky et al. [48] compared a traditional controller solution with a camera-based hand tracking interface, revealing a higher performance, usability and user preference for the handheld controller. These results may suggest that it is still challenging to design hand-tracking interfaces due to detection errors caused by partial or total occlusion of the user's hands. Despite some limitations, there are already devices that perform satisfactory hand tracking. section 2.2.2 discusses hand representation in VR in more detail.

Tangible environments in VR allow a tighter association between physical objects and their virtual representation. Developing tangible interfaces in VEs usually requires additional hardware to track physical objects' position and rotation. Various systems have been proposed, from active (instrumented with sensors) to passive haptic.

Harley et al. [49] proposed a system for diegetic tangible objects in VR narratives (Figure 2.2). A device-agnostic sensor unit is attached to the physical object to be tracked, featuring active and passive haptics. In this work, the tactile sense's inclusion helped immerse the user in the narratives being told.

Arora et al. [51] proposed an alternative to conventional VR controllers, which can limit the design of virtual experiences. VirtualBricks is a LEGO-based toolkit to create custom controllers for VR, enabling actions such as shooting targets using a gun or catching a fish by rotating the fishing reel.

De Tingyu et al. [50], and Carvalheiro et al. [47] proposed a different approach for tangible object tracking. De Tingyu et al. [50] ensures whenever users grasp the physical

Figure 2.2: Diegetic tangible objects for VR narratives [49].

object, they also hold the virtual object by using a Bonita Vicon system, as shown in Figure 2.3. The system tracks subjects' thumb and index fingertips using markers placed on the dorsal side of their fingers. A 3D-printed support was used to ensure a good matching between the positions of the tangible object and the virtual object.

In turn, Carvalheiro et al. [47] developed a VE where a blue spherical object is tracked by the RGB sensor of a Kinect v2 camera. Another marker-based solution, but this time for smartphone-based VR, was proposed by Cardoso and Ribeiro [52]. The system does not require additional hardware instrumentation. The smartphone used to display the VE also detects a physical book's pages through marker-based computer vision. Figure 2.4 illustrates the book used with the markers that are tracked by the smartphone to render the virtual book.

The covered examples make it possible to verify that the integration of physical objects into VEs can be done using different approaches. Typically, the methods used involve adding hardware devices to the standard VR setup, as was the case in the experiments conducted by Harley et al. [49] and De Tingyu et al. [50]. The approaches freer of additional devices and circuits fall on computer vision technology, such as the system suggested by

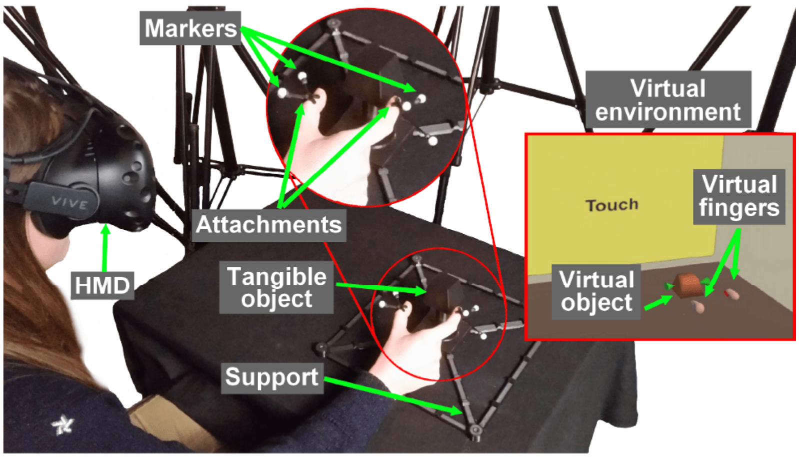


Figure 2.3: A Bonita Vicon system was used to track the thumb and index fingertips using markers placed on the dorsal side of their finger [50].

Figure 2.4: Tangible VR book applied to cultural heritage exploration [52]. The markers are tracked using computer vision algorithms.

Cardoso and Ribeiro [52]. This last approach may prove more flexible to changing or adding different tangible objects to the system, compared to methods that rely on circuits purposely designed for the characteristic of a specific object.

2.2 Space in VR

Immersive interfaces offer powerful experiences based on visualization and interaction design transforming the sense of space. Thus, VR seems to have the ideal characteristics to study human spatial perception since it is easy to manipulate aspects of the virtual world that would be difficult to change in the real world. In particular, exploring the perception of distances and sizes is made easier because it is possible to introduce subtle distortions and analyse whether they improve task performance while preserving presence.

As will be discussed in the following sections, studies have revealed that the human brain does not perceive the virtual world in the same way as the real world. Even when the virtual space is drawn on the scale of the real world, there is a strong tendency for distance, depth, and size to be underestimated. Besides these findings revealing interest in areas of psychology, they are equally important insights in the design of VR applications. Interaction techniques should be shaped according to the user's perception when wearing the HMD so that tasks performed in the VE (e.g. grasping objects, walking, selecting) are not misleading.

This section starts then by addressing some factors that influence the perception of space in VR. Afterwards, different interaction and spatial distortion techniques will be discussed as well as their impact on UX.

2.2.1 Space Perception

Studies on the perception of space in VR have revealed that the human brain perceives the real and virtual space differently, presenting a great tendency to underestimate the size and distances when wearing the HMD [53]. The following is a sample of studies that reveal the challenges inherent in the closely related perception of depth and size in VEs.

Depth Perception

Screen-constrained visualizations, such as traditional desktop displays, are based on rendering on 2D screens with no stereo depth cues and have no viewpoint correlation, i.e. when the user moves around, the viewpoint of the virtual scene remains constant. A stereoscopic window, although also constrained to a 2D screen, offers a view with stereoscopic depth cues and high viewpoint correlation, that is, the viewpoint is rendered according to the user's point of view.

In VR, the stereoscopic displays mimic natural human depth perception. The brain extracts information from the state and stimuli the eyes perceive to generate depth information and stereoscopic images. These bits of information are called depth cues. Visual depth perception involves the mental combination of monocular and binocular visual cues to determine the 3D shapes of objects in the world, their spatial arrangements relative to each other, and their locations relative to oneself [54]. Monocular cues require only one eye to perceive depth and are easily seen in 2D representations. Relative size, occlusion, shading, and texture are examples of monocular depth cues represented in paintings or videos. Binocular cues require both eyes to perceive an object in 3D space, making it easier for the human brain to calculate the depth and distance of objects accurately. Stereoscopic 3D displays can allow both monocular and binocular depth cues to coexist in a single display system.

Depth perception has been the subject of several studies associated with VE, and the most consensual conclusion is that depth and size in VR are underestimated [15]. Further on this topic, some studies investigated the effect of colour on depth perception. The results have indicated that warm colours are perceived as nearer to the user while cold colours are perceived further away [55, 56]. There is also evidences that luminance bright colours are perceived as nearer to the user, while dark colours are perceived as further [57].

Size Perception

Depth perception can influence object size since size perception mainly depends on depth cues. As seen in Figure 2.5, although the two objects are the same size on the retina, the near object seems smaller. In VR, the size of the objects is usually underestimated; when virtual and real objects are of the same size on the retina, the virtual one is perceived as nearer, so it also should be perceived as smaller [58].

Even when virtual objects are designed to the scale of physical objects, this distorted perception can happen. In applications that aim to realistically simulate the real world, such as training scenarios in medicine or architecture, it is crucial to ensure that users have the correct perception of the size. To this end, it is up to researchers and designers to understand how the human brain works in these cases and which design techniques should be applied to correct size perception in VR.

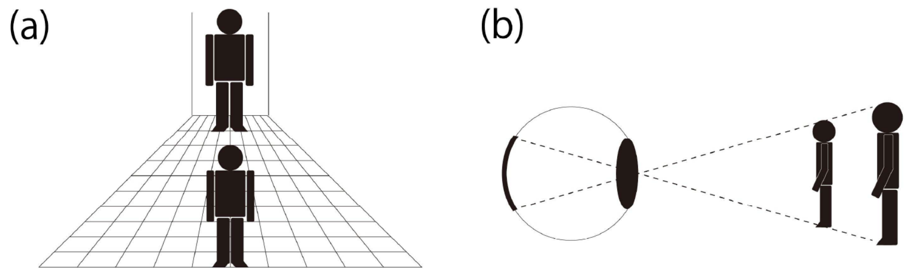


Figure 2.5: Relationship between depth and size [58].

Ogawa et al. [58] studied the relationship between object and hand size perception in VR. Their findings confirmed that users perceive virtual hands as larger and objects as smaller in VEs. However, when hands interact with objects, the avatar body is used as a metric to scale the apparent sizes of objects, as suggested by the effect of body-based scaling. Also, in an attempt to ensure the correct perception of virtual sizes, Katzakis et al. [16] suggest that haptic feedback can complement the visual perception. The experiment conducted in this study compared the size (small, medium and large) of a visual and haptic sphere (using a haptic device). The results show a dominant functional priority of the visual size perception since participants tended to judge the visual size as larger than the haptic sizes, even though they were the same. Additionally, participants demonstrated a typical tendency for overestimating the smaller haptic size but underestimating the larger haptic size.

Siqueira et al. [59] also revealed the tendency of users to rely their perception on visual information. The authors conducted a study to evaluate the accuracy in size precession under three conditions: Vision-only, Haptics-only and Vision and Haptics. Comparing the Vision-only and Haptics-only conditions, as expected, the accuracy was better in the visual condition; however, in both situations, participants tended to overestimate the size of tangible components. Notwithstanding, contrary to what was expected, when both visual and haptic information were presented, participants were less accurate in size estimation than in the vision-only condition. This conclusion goes against the reasonable expectation that more diverse perceptual information channels enhance size estimation accuracy, highlighting the potential for perceptual conflicts when both visual and haptic information is provided in VR.

These last three studies [16, 58, 59] presented are only a sample of the studies conducted on size perception in VR. Although they show different experiences and results, both highlighted the visual predominance of the human being and that more work is needed to thoroughly investigate the influence of this perceptual conflict on size estimation in VR. These findings provide important implications for the 3D vision-only or visuo-haptic HCI design.

2.2.2 Virtual Hands

Some tasks in VR demand hands representation, or at least some reference about their position in the virtual space. Select, grasp, or move tasks can be easily satisfied through ray-casting techniques or by representing the handheld controller in the virtual world. However, controller-free tasks usually require a more realistic representation of the hands to enhance **body ownership**, i.e., feeling that the artificial body is one's own body and the source of sensations.

The Rubber Hand Illusion, initially presented by Botvinick and Cohen [7], was a pioneering study on the virtual body and how the human brain resolves visual and perceptual stimuli, leading to a rubber limb's appropriation. Further studies have shown that the virtual hand's structural and appearance differences might affect the sense of ownership, presence and performance.

Lin et al. [8] compared six geometric models (Figure 2.6) with distinct appearances to investigate the effects of different realism levels, render styles, and sensitivities to pain on the virtual hand illusion. Experiment results indicate that the illusion can be created for any model, even for an abstract model such as a wooden block. Nevertheless, the effect is perceived weakest for abstract models and strongest for realistic human hand models.

In another experiment that also compared different representations of the hands, the results were opposite to those obtained by Lin et al. Grubert et al. [9] studied the effect of different representations of the user's hands on typing performance (Figure 2.7). The results revealed a high input rate, low error rate and user preference for a minimalistic fingertips model. In contrast, a more realistic hand representation had a higher error rate. It suggests that minimalistic representation may enhance keyboard visibility while realistic hands do not allow as much visibility.

Elbehery et al. [10] investigated how hand representation affects UX and presence in a VE with passive haptic interaction. In this experiment, three conditions were compared: no hands, rigid 3D model and rigid 3D model with snapping mechanism. The virtual hands only performed basic grasping operations depending on how close they were to objects. Comparing the three models, the results indicate that a 3D model paired with a

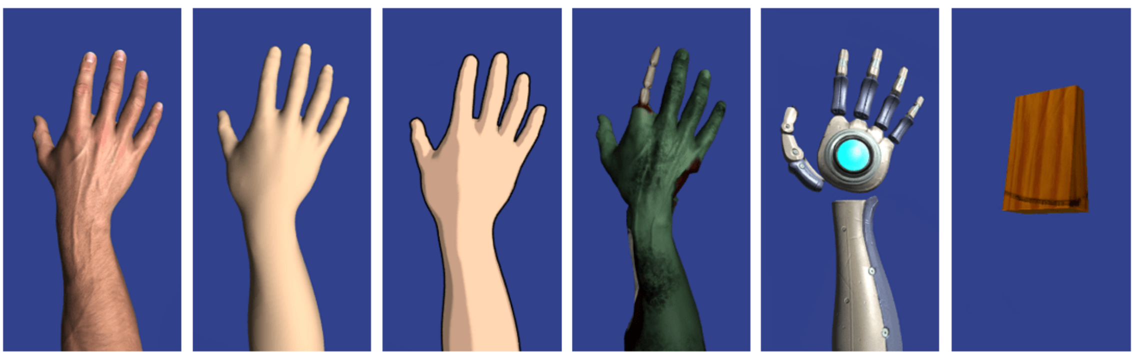


Figure 2.6: Six hand models used in the experiment conducted by Lin et al. [8] to study the body ownership illusion.

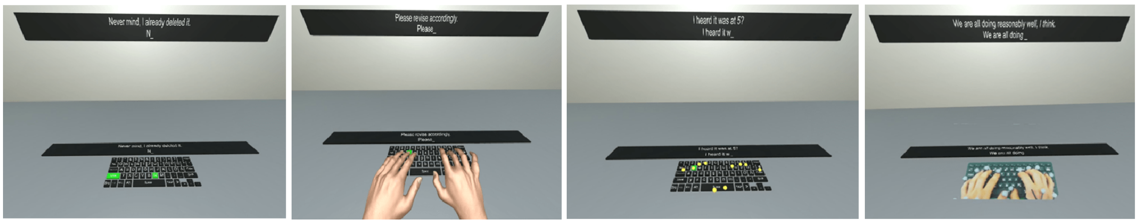


Figure 2.7: The four conditions studied by Grubert et al. [9] to analyse the effect of hand representation in typing tasks.

snapping mechanism significantly increases presence and UX.

Although there are many more studies on hand representation in VR, from the experiments conducted by Lin et al. [8], Grubert et al. [9] and Elbehery et al. [10], you can see no consensus. A realistic human hand model can increase body ownership; however, it can impair performance if it is not suitable for the task at hand, as was the case with Grubert et al. [9].

Hand representation technologies

Some HMDs (e.g., Oculus Quest 2, HTC Vive Cosmos) have built-in cameras capable to track users' hands. As an alternative to embedded sensors, hands can be captured by two main approaches: optical trackers or inertial trackers [60]. Optical trackers include vision-based systems such as the Microsoft Kinect or the LeapMotion. These systems' advantages are that they are cheap and easy to use (plug and play). On the other hand, they may not be suitable for applications where the hands are not always clearly visible. Inertial trackers or data gloves offer a more accurate representation; however, they are more expensive, require proper calibration and data filtering to obtain acceptable tracking performance.

Other more invasive approaches rely on devices that are attached to the user's hand (e.g., Vive trackers, gloves, Vicon Bonita system) or camera-based solutions that use computer vision to detect markers previously placed on the user's hands [10, 52, 61]. Figure 2.8 illustrates some of the approaches mentioned.

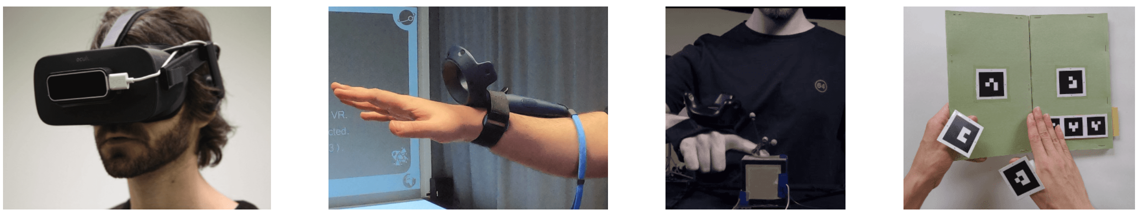


Figure 2.8: Hand tracking approaches (respectively from left to right): Leap Motion Controller [48], Vive controller strapped to the wrists [10], Vive tracker and Bonita Vicon system [61], marker-based system [52]

2.2.3 Locomotion Techniques

In VR it is possible to simulate VE with large, and potentially infinite, visual areas, without leaving the confines of a small physical area. Due to tracking space constraints, physical movement often needs to be replaced by artificial locomotion techniques. Figure 2.9 illustrates three techniques of locomotion in VR. Walking in VR has been desirable due to its ability to elicit higher presence, compared to other techniques like walk-in-place and joystick-based locomotion. However, walk naturally in VR requires some tracking space for the user to move, not proving to be suitable for at-home VR experiences. Other options enable walking in larger virtual areas without exiting the smaller tracking area [1]. For example, redirected walking and resetting allow room-scaled walking while steering the user away from the tracking space boundaries through continuous manipulation of mapping between physical and virtual rotations.

Redirected walking takes advantage of humans' inability to detect small discrepancies between visual and proprioceptive sensory information during navigation. By injecting appropriate mismatches between a user's physical movement and its visual consequence, a user can be steered imperceptibly towards the center of the tracking space and away from physical obstacles. The basic implementation of this technique involves rotating the visual scene about a vertical axis centered on the user's head so that, when attempting to walk in a visually straight path, the user must veer physically to reach his goal. Figure 2.10 describes a simple experiment studied by Hodgson et al. [3] in which the participant's task was to answer simple mathematical questions while walking along a (virtually) straight path. At the end of the experiment, participants were asked to point to the starting location, and all indicated different starting points than the correct one. This result highlights that users can be easily redirected in VEs through space morphing without realizing it.

VR sickness symptoms continue to be an inherent challenge in virtual space navigation, especially when the user is in constant motion. Teleportation is the most common form of navigation in VR, allowing the user to move meters in virtual space, without

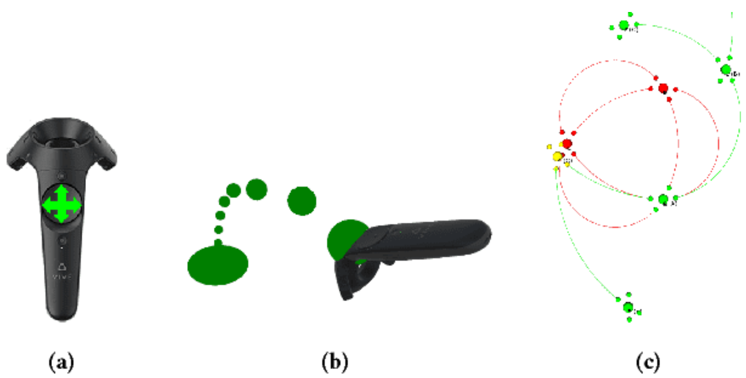


Figure 2.9: Three locomotion techniques: (a) Joystick-based navigation, (b) Teleportation, and (b) Redirected walking. [2]

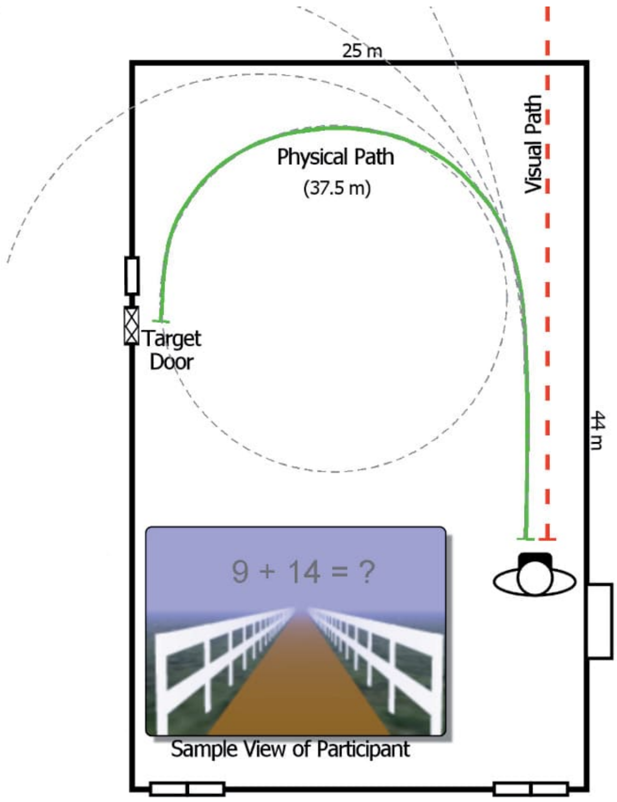


Figure 2.10: Schematic representation of physical (solid green) and virtual (dashed red) paths traveled by users in the study of Hodgson et al. [3].

moving in the real world. The user points the controller toward a position in the virtual world and presses a button to instantly move there (Figure 2.9b). Since it discontinuously translates the viewpoint, instant teleportation does not generate any optical flow, and thus reduces the risk of vection (the sensation of body movement in space produced purely by visual stimulation) induced VR sickness [1]. As a drawback, teleportation can cause disorientation and break in presence [62]. To reduce these negative effects, variations of teleportation have been proposed to allow a more continuous displacement. For example, the company Aldin introduced Telepath[1], a locomotion path-based system that allowed users to move smoothly along a hand-drawn path at walking speed (Figure 2.11). This solution of drawing a guideline on the ground may support the hypothesis that reference points contribute positively to the user's self-location, counteracting disorientation when the surrounding environment is deformed or moving.

2.2.4 Non-Euclidean Spaces

Although human beings are used to living in a three-dimensional (3D) Euclidean space, the properties of non-Euclidean spaces have revealed their applicability in games and large dataset visualization. Hyperbolic geometry, a non-Euclidean geometry, rejects the

[1]Telepath VR Locomotion: https://medium.com/aldin-dynamics/introduction-to-the-telepath-vr-locomotion-system-38b8e992b7d4 - Last accessed 14/11/2021

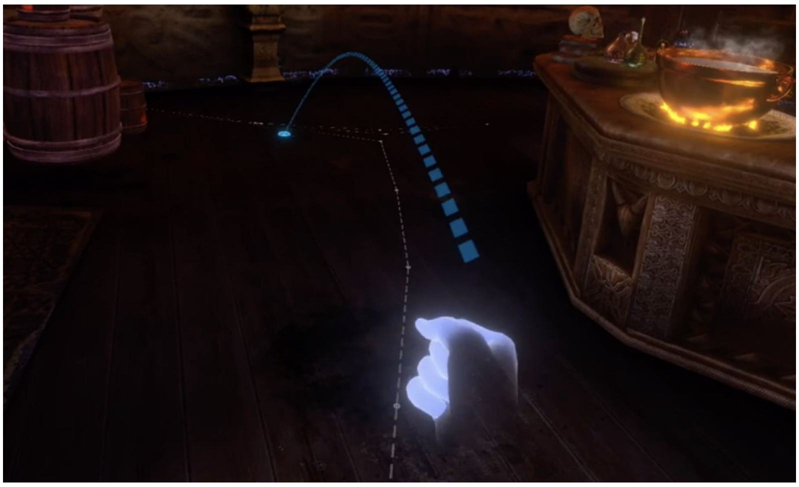


Figure 2.11: Telepath VR locomotion system introduced by Aldin company for enhance presence, physical freedom and reduce the symptoms of motion sickness.

parallel postulate that stated that through a point not on a given line, there is exactly one line parallel to the given line. In hyperbolic geometry, through a point not on a given line, there are at least two lines parallel to the given line. This property makes it possible to access much more area within a given distance.

Celinska et al. and Kopczynski [63] used the hyperbolic properties to create a diagram of the most popular programming languages on GitHub to show the proximity of languages often used together (Figure 2.12). The power to fit arbitrarily large trees in hyperbolic space without distortion makes it valuable for portraying large hierarchical datasets.

Kopczynski et al. [64] developed the HyperRogue game to investigate the mathematical properties of hyperbolic geometry thoroughly. They suggest the applicability of these

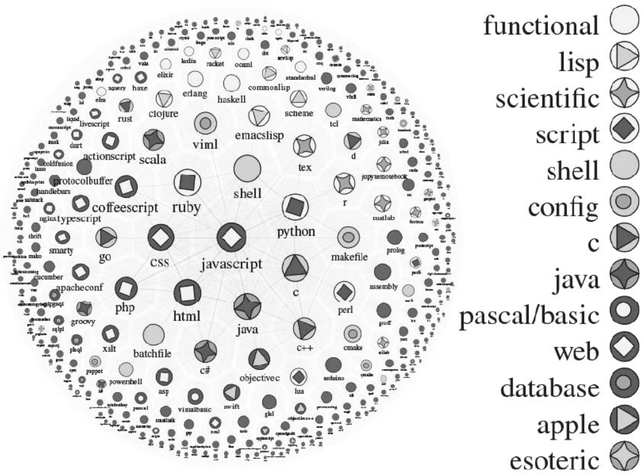


Figure 2.12: Diagram of programming languages dispersed by level of relation in a hyperbolic plane [63].

Figure 2.13: VR simulation developed in hyperbolic space [24].

spaces in mathematical research, education, and game design. An exponential amount of space can be used to create challenging levels for users, which Euclidean space does not allow to simulate. On the other hand, players can use the curvature of hyperbolic geometry to evade enemies or dodge obstacles more intuitively.

A group of mathematicians and physicists explored non-Euclidean geometry through a VR simulation. Hart et al. [24] aimed to show the utility of 3D non-euclidean spaces giving people the ability to move through those spaces with their bodies. Figure 2.13 shows the virtual world created. The user can enter each of the numerous holes in the virtual world, even though he is limited to the rectangular area marked on the floor in the real world. Comparing the images of the real and virtual worlds highlights the ability of non-Euclidean geometry to create the feeling of wider spaces. The VE is composed of geometric shapes that, once inside them, the user has the possibility to choose one of six paths, due to the constant negative curvature of this geometry. The image on the right shows the six cavities in a top view.

Research on navigation in non-Euclidean spaces has revealed the benefits of hyperbolic geometry and its potential applicability in VEs. However, there is still a gap in studying the relevance of these benefits in simple, natural tasks in VR. Pisani et al. [12] built a minimalist VR game with comparable Euclidean and hyperbolic levels to analyse whether people can comfortably navigate in hyperbolic space. The participants' task was to collect spheres along a path. When the sphere was collected (turned green), a redirection was applied to the user's position. This redirection was implemented using two approaches - Euclidean and hyperbolic - to compare the participants' performance

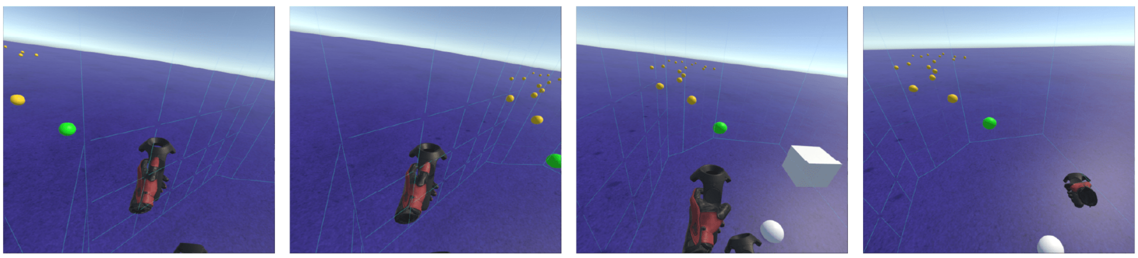


Figure 2.14: Task of collecting spheres under redirected walking using Euclidean and hyperbolic functions [12].

in each space. Figure 2.14 shows some screenshots of the minimalist environment developed for the experiment. Although the authors have not evidenced statistical results on performance, their results suggest people can navigate in hyperbolic VEs without significant disorientation. Moreover, users may feel more intuitive navigation in some circumstances, like navigating ranching structures.

2.3 Time in VR

An enjoyable VR experience does not rely exclusively on high-quality realistic graphics. Immersive simulations require a prompt, fluent and synchronized response of the system [65]. Latency is a crucial design parameter for any VR system since frame update rates significantly affect the sense of presence and efficiency of performed tasks in VEs. In high-precision tasks, remote communication or collaborative environments, significant latency can make the job frustrating or not feasible. Thus, it is necessary to create responsive applications for dynamic and seamless user interaction.

Studying time in VR brings up the negative impact that the delay can have on the UX. However, time can be manipulated in ways that prove to be useful, such as playback or cancelling actions. For example, when a baseball player hits the ball in a sports training context, it is not always necessary to see the whole trajectory to understand if the ball will hit the desired spot. It may be interesting to speed up or even cancel the action to save time. Playback review can also help players improve their technique [22].

This section aims to address time perception in VR and the adverse effects of latency in a virtual context.

2.3.1 Time Perception in VR

A large body of literature has analysed space perception in VR, and some of these studies were discussed in section 2.2.1. Although it is common knowledge that games and interactive applications often cause people to lose track of time, there is still a scarcity of knowledge about how users perceive time in VE. VR applications distract users from the real world, keeping them amused performing tasks in an environment that is often more stimulating than everyday life tasks. VR attention diversion capabilities have already been used on patients during chemotherapy sessions, resulting in an elapsed time compression effect [66].

The sense of time takes the human being to feel present "here and now”. Friston et al. [67] believe that the study of time perception in VEs can be used for diagnosis and therapy of psychiatric conditions related to altered time perception, e.g. as the feeling of being "stuck in time". Their research proposes to study the waiting time perception in VR. The experience consisted of leaving the participant in a room, sitting on a chair, and immersed in a VE while the researchers pretended to be having technical problems. After 7.5 minutes, they would return to the room and ask the participant how long he/she had been waiting. This experiment was studied under two conditions: with and without the participant's body through an avatar. The results suggest that waiting time estimations can be affected by the absence of an avatar. Performing the experience with a 3D-model avatar resulted in time perception of 6.7 minutes. In comparison, the same experience without an avatar model resulted in an average time of 7.8 minutes.

In the same research subject, Schatzschneider et al. [68] explore the effects of manipulated zeitgebers, cognitive load, and immersion on time estimation of spatiotemporal perception in immersive VEs. The results show that controlling external zeitgebers through the virtual sun movement significantly affected time judgments.

Both studies ended their conclusions by highlighting the importance of understanding how time is perceived in VR. This topic has great potential to stimulate new research directions, mainly when numerous consumers use VR technology for long periods of time.

2.3.2 Latency in VR

As mentioned in section 2.1.2, latency can cause cybersickness by creating a mismatch between the visual and vestibular systems. Thus, high frame rates and low latency are required to create a true sense of presence in an interactive VR experience. Creating low latency systems can be particularly challenging in VR applications since the processing of video signals to generate the visual HMD scene is very CPU-consuming. Furthermore, the rendering costs per pixel have continued to rise with increasing demand for more realistic computer-generated imagery.

Therefore, it is essential establishing a tolerable latency level to optimize system performance, leverage presence and avoid symptoms of discomfort. Albert et al. [69] explored the effect of latency for foveated rendering, a promising optimization for VR graphics that generally requires accurate and low-latency eye tracking to ensure correctness. Their experiment results suggested that latency of 50-70 ms could be tolerated by participants and, consequently, the low-latency requirements may be relaxed. Many other studies have been conducted on the topic of latency in VR, and a few will be referenced in this section.

Non-constant frame rates can have a more negative impact than constant frame rates [65]. The human being easily adapts to slow system responses, but when the update does not come at the expected timestamp (even delayed), human senses and brain get disoriented. Park et al. [70] show that with increased latency, humans adopt a move-and-wait strategy, waiting to let their views synchronize before continuing performing their tasks. This strategy can be minimized in tangible VEs since users, even not having immediate visual feedback, have haptic feedback and can use **proprioception**, i.e., the sense of self-movement and body position. In the case of VEs with haptic feedback, it is also crucial to ensure synchrony between visual and tactile stimuli to provide the user with a sense of body ownership and realistic experiences.

Since the system developed in this dissertation is a tangible VE, we surveyed the latency tolerable by users in VEs with haptic feedback. Table 2.2 synthesizes the most relevant results at the task diversity level. The *Tolerable Delay* column shows the maximum latency imperceptible to the user and/or latency that does not significantly impact task performance, either in completion time or discomfort symptoms caused.

The results of Jay et al. [31] highlight that, although participants could detect low latency (50 ms), their performance is only affected by higher values (100 ms). Brunnström et al. [17] also suggested that although delays starting at 400 ms already implied effects on responsiveness quality, more pronounced effects were only evident for delays of 800 ms. That said, the effort should not just be focused on setting latency imperceptible to users. It is equally relevant to define from which latency the task performance is significantly affected, be it in completion time or discomfort symptoms.

The experiments shown in Table 2.2 suggest different results, which indicate that the temporal accuracy of visual-haptic interfaces had to meet requirements tailored to the application and tasks at hand.

Table 2.2: Survey of tolerable latency in VEs with haptic feedback.

Authors	*Task*	*Tolerable Delay*
Luca and Mahnan [26]	Tap an object and determine which stimulus occurred first (visual or haptic)	Visual feedback: 15 ms Haptic feedback: 50 ms
Hirsh and Sherrick [27]	Order which stimuli occurred first on asynchronous visual–tactile stimuli; tested with well-trained participants	Visual feedback: 20 ms Haptic feedback: 20 ms
Ingrid et al. [28]	Judge if a object collided with a virtual wall simultaneously with a force felt through a force feedback joystick.	Visual feedback: 59 ms Haptic feedback: 44 ms
Kaaresoja et al. [29]	Employing a touchscreen, judge if touch was synchronous with haptic and visual feedback.	Visual feedback: 85 ms Haptic feedback: 50 ms
Jay et al. [30]	Tap a target as quickly and accurately as possible.	Visual feedback: 69 ms Haptic feedback: 200 ms
Jay et al. [31]	Target acquisition task in collaborative VE under different visual feedback delay.	Errors increase from 25 ms; Perceive latency from 50 ms; Users slow their movements from 100 ms.
Brunnström et al. [17]	Controlling a crane with haptic feedback from a joystick under different visual feedback delay.	Weak effects for 400 ms; Strong effects for 800 ms.

2.4 Summary

This chapter started by contextualizing the application of VR and some concepts inherent to HCI in VEs. Some methods of evaluating UX in virtual experiences were presented, focusing on subjective methods, i.e., questionnaires.

The two key topics of this dissertation were addressed: space and time. To better understand the perception of space in VR, redirected walking techniques that take advantage of the human inability to detect slight differences between visual and motor senses were explored. We also presented works that explore the interaction in tangible

VEs, where the tactile sense can contribute to more immersive virtual experiences. In addition, different experimental setups were presented that makes it possible to integrate real-world objects into the virtual world displayed when used through the HMD.

The perception of time was addressed, with primary emphasis on the human ability to easily adapt to latency conditions. In this sense, a survey on human tolerance to delay in environments with haptic feedback was elaborated.

The studies raised in this chapter were essential to understand the human spatial and temporal perception in VR and to discover gaps that deserve further investigation. The spatiotemporal morphing scenarios addressed in this dissertation will be presented in the next chapter based on the related work surveyed in this preliminary state-of-the-art review phase.

3

Analysis and System Design

In order to test the space and time morphing scenarios, it was necessary to have a functional system to explore the transformations. The VR Lab emerges to tackle this purpose, accompanied by a case study and tasks to incorporate the different space and time conditions.

This chapter begins by justifying the morphing scenarios chosen based on the literature reviewed in the previous chapter. The system requirements are then described, listing the main features that the VR Lab should include.

The case study was shaped to the requirements, giving rise to a preliminary prototype. The weaknesses revealed in the initial tests made it possible to draw conclusions that led to the design of the two tasks used in the VR Lab: Target Game and Puzzle Game. Each of the tasks is described, as well as what each of them intends to assess.

3.1 Morphing Scenery

Space and time can be manipulated in countless ways in a VR context. Therefore, it was necessary to select a restricted number of scenarios to study in more detail.

After analysing the related works on the topics of space and time in VR, we selected four themes that proved interesting to be studied in the proposed tangible VR Lab. Next, we present the motivations of the four scenarios that gave rise to the research questions set out in section 1.2 and how we intend to address each of them.

Spatial Function Scenario

Linearly enlarging a Euclidean virtual space preserves the geometric properties that human beings are used to experiencing in their everyday actions. However, hyperbolic spaces' properties make it easy to create the illusion of larger spaces with different precision of movements along the play area. It can be helpful depending on the motion precision required by the task. As an example, we can have a higher precision close to the user and wider movements farther away. Furthermore, the negative curvature of hyperbolic geometry can make it easier for players to escape enemies in a video game more intuitively. As presented in section 2.2.4, research on non-Euclidean navigation in VR [12, 24, 25] reveals geometric benefits of non-Euclidean environments and suggests that people can comfortably navigate in hyperbolic space. However, there is still a gap in studying the applicability of these benefits in basic tasks in VEs.

To bridge this gap, we propose a scenario where it is possible to increase the virtual playing area in two ways: using Euclidean geometry and hyperbolic geometry. Through basic tasks, we intend to find out if the performance and ease with which users accomplish the jobs are the same for the two approaches.

Object Size Scenario

Human spatial perception relies mainly on visual information, which has revealed a tendency to underestimate space in VR (section 2.2.1). Contrary to the reasonable expectation that the introduction of haptic information could help the user to estimate distances correctly, it is not always verified. The experience conducted by Siqueira et al. [59] revealed a potential conflict between visual and haptic stimuli, even when the virtual and haptic objects are the same size. To further explore this topic, this scenario aims to study the performance and user preference in cases of incongruence between the size of virtual and haptic objects.

To tackle this motivation, we propose changing the virtual object's size in three ways - small, normal, large -, keeping the size of the physical object constant (i.e. normal). The extracted results can contribute as guidelines in the design of visuo-haptic applications. It is hoped to draw conclusions about whether virtual objects must be strictly equal to physical objects to provide suitable interaction. Or otherwise, even in case of a visuo-haptic incongruity, the feasibility and performance are preserved.

Hand Model Scenario

By allowing the user to interact with objects with bare hands, tangible interfaces supplement visual stimuli with information about physical objects' shape, size, relative position and orientation. In some cases, haptic cues do not dispense with the representation of hands or at least some indication of their location in the virtual space. Although realistic virtual human hands can leverage embodiment, it is not always the best approach in some tasks. From the examples discussed in section 2.2.2, minimalistic or abstract representation of the hands can be sufficient to help the user perform the tasks.

This scenario thus aims to analyse whether hand representation, in a tangible VE, improves performance or at least helps the user feel more comfortable performing the task. To this end, tasks will be performed under different hand models: no hands, a realistic model of the human hands, and an abstract model. The three conditions will be compared for performance and user preference.

Time Morphing Scenario

Establishing tolerable latency in VR systems can be valuable in relaxing rendering requirements and saving resources to optimize system performance. Section 2.3.2 presents a brief survey of studies on user tolerable latency in tangible VEs. The results differ greatly depending on the task and the briefing given to users before the experience. When participants know in advance that they will perform tasks with delay, part of their attention will focus on detecting minimum delay values that otherwise would not be noticed nor interfere with performance.

This scenario proposes to have the user perform tasks with tangible objects under different delay conditions. Latency will be applied to the visual feedback of the virtual objects, and participants will not know in advance that they will perform tasks under delay conditions. The goal is to analyse for which values latency affects performance and the ease of the task.

3.2 Requirements

To follow the motivations proposed in section 3.1 and recall the research questions stated in section 1.2, this section presents the main requirements for the system design and implementation.

This research proposes to study the users' adaptability to different spatiotemporal conditions. Therefore, designing an immersive virtual experience with simple challenges based on basic object manipulation tasks was essential to avoid bias from discomfort symptoms or task complexity.

The system was designed to create a VE with support for passive haptic feedback to leverage the sense of presence and immersion. In this way, users must see the virtual world through the HMD and control the virtual objects handling the tangible objects with their bare hands. The haptic feedback enables a more natural and intuitive interaction that does not require operating the handheld controllers. To further promote the sense of presence, all the questions asked to the user during the experience must be displayed inside the VE to minimize breaks in presence, as suggested by Putze et al. [39].

In summary, the core requirements of the system are as follows:

- Support interaction with tangible objects the user can easily manipulate with bare hands. The tracking mechanism should require minimal additional hardware devices to be easily adaptable to any tangible object.
- Simulate different space conditions. For this research, these conditions include creating Euclidean and non-Euclidean spaces, changing the size of tangible objects, and changing the virtual hand representation.
- Simulate different time conditions. For this research, these conditions include different levels of visual delay applied to the movement of tangible objects.

- Include simple tasks capable of embedding the space and time conditions under study.
- Allow displaying questionnaires inside the VE.
- Include a User Interface (UI) for the researcher to manage the spatiotemporal conditions presented to the user.

3.3 Case Study

It was necessary to establish a case study covering the specified requirements. For this purpose, the creation of a virtual room with tangible objects was envisaged. This room should hold different scenarios presented to users to study their adaptability to different morphing conditions.

The VE should be able to distract the user from the real world, immersing him/her in an ample and pleasant space. Thus, the chosen scene recreates a relaxing open space in an oriental country where the user could perform the task, sitting at a desk, while listening to nature sounds.

Spatial and temporal transformations would be essentially applied to the virtual representation of the tangible objects with which users would have to interact to perform tasks. The tasks consisted of simple games familiar to the users so that the results would not be biased by complexity. The aim was not to assess users' skill but rather their adaptation to different spatiotemporal conditions.

Hence, in the real world, the user would be sitting in front of a standard table. On the table would be the tangible objects that he/she would have to handle to perform the task. By putting on the HMD, the user should immerse into an open place, with background sounds of nature. In front, he/she should also find a table, but much more spacious than the physical table. On the table should also be the virtual representation of the tangible objects.

The experiment would consist of presenting games to the user that involve handling tangible objects. The conditions under which the users performed these games varied depending on the morphing scenario under study.

3.4 Experimental Setup and Architecture

Having settled on the requirements and the case study, the designed system should accurately track tangible objects and display them within the VE. The approach chosen to track the objects should be able to detect objects with different shapes and sizes without requiring much additional hardware beyond the standard required in VR setups. That being said, a marker-based tracking mechanism was chosen. It only required a simple webcam to detect any object previously marked with a target image, similar to the method

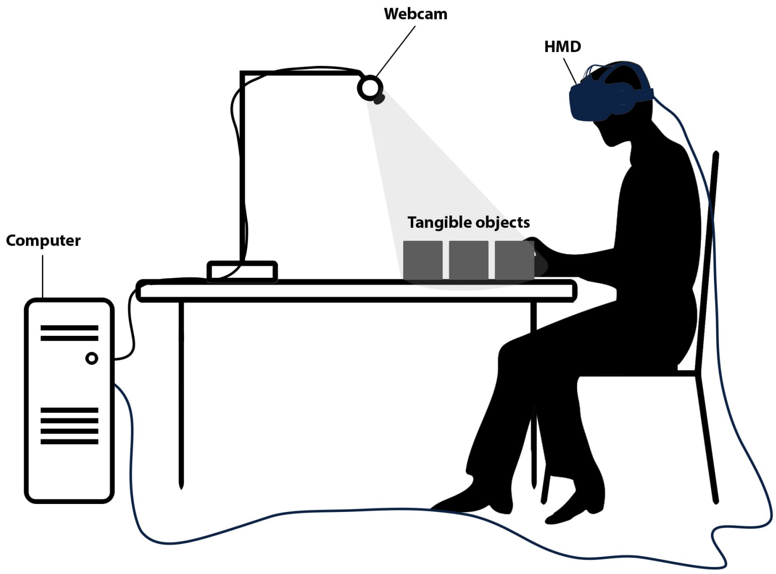


Figure 3.1: Experimental setup.

typically used in AR applications. For stable tracking, the webcam should be fixed in the same place during the whole experiment.

Figure 3.1 presents a sketch of the experimental setup adopted. The user sits in front of a table interacting with physical objects while viewing their virtual representation through the HMD.

Figure 3.2 presents a high-level architecture that shows the connection of the main components of the system. The user receives visual feedback through the HMD and passive haptic feedback by interacting with tangible objects. The objects are tracked by a marker-based application, which uses a webcam and computer vision technology to recognize and track in real-time the planar images stuck to the objects. The position and orientation gathered in tracking are manipulated in the morphing modules, whose output is the position and orientation of the respective virtual object under a given spatiotemporal morphing condition. The VR application is then responsible for rendering

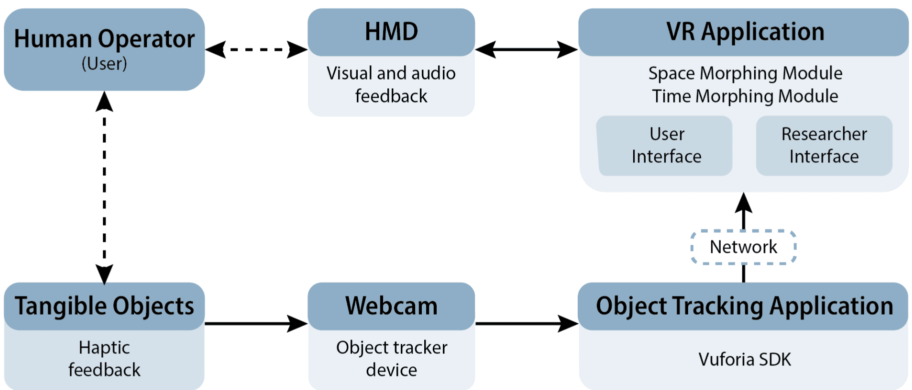


Figure 3.2: High level architecture.

the scene displayed on the HMD and also includes a UI so that the researcher can manage through the computer the morphing scenarios presented to the user at each moment.

3.5 Preliminary Prototype

The challenge initially designed was Tangram (Figure 3.3), a seven-piece puzzle well-known to most people, allowing intuitive interaction with the tangible pieces of the puzzle. Initial tests revealed that Tangram, with its original characteristics, gave rise to several tracking problems.

This first prototype was essentially intended to test the integration between the VR application and tangible objects. Decisions made to mitigate the problems that arose during initial testing led to simplifying the traditional Tangram game until a final design was achieved. The implemented games are presented in the next section (section 3.6), but first, we will describe the main challenges revealed with this prototype, followed by the trade-off adopted.

Shape and size of objects: Although the puzzle presented simple geometric shapes, the pieces had little height, which led the users to grab or drag the pieces by covering the markers with their hands, causing many tracking breaks. The solution to this problem was to increase the size of the pieces, especially their height. In this way, users could move the pieces simply by dragging them along their lateral sides without covering the marker image stuck to the upper side facing the camera. Furthermore, increasing the size of the pieces made it possible to use larger markers, which were more visible and better tracked by the camera.

Distance between webcam and table: The webcam had to be placed at a height of about 80 cm for all seven pieces to be tracked. At this height, the camera could not always detect in detail the markers, leading to tracking breaks. The solution was to shorten the distance between the webcam and the table; however, this significantly reduced the

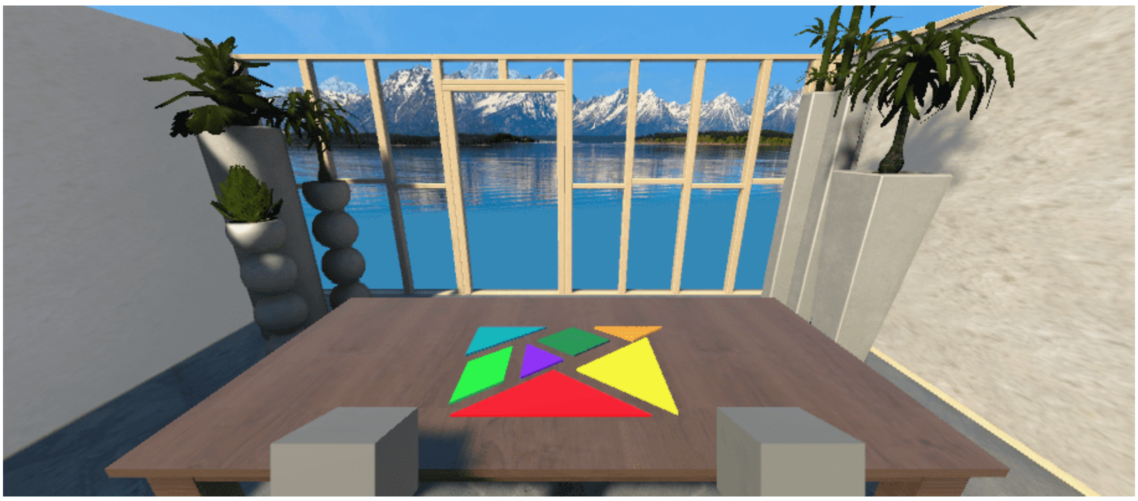


Figure 3.3: The preliminary VR Lab prototype featured the Tangram game.

tracked viewing area, giving the user little room to move the pieces around without them often being out of camera range.

Objects size and webcam-table distance trade-off: It was necessary to define a trade-off between the objects size and the distance between the webcam and the table to ensure accurate tracking. The objects dimensions were 10×10×10 cm, enabling the user to handle each object with only one hand, without hiding the upper side. The markers dimension was also 10×10 cm to be properly detected. The webcam was placed at the height of 70 cm, which showed to be, after several initial tests, the maximum height that allowed faultless tracking. The webcam covers a table area of about 60×40 cm at this height, which proved to be a small area to move seven objects loosely. For this reason, we chose to use a reduced version of the Tangram, with only three pieces: one cube and two triangular prisms (right triangles). In this way, the tracking was accurate, and the user could move objects without the objects constantly colliding with each other or moving out of the camera's range.

Figure 3.4 shows the target images chosen for each object and the movements allowed for moving objects around the playing area. The image targets choice will be detailed later in section 4.3.1. The user can move the object along the x-axis and z-axis and rotate it about the y-axis (vertical). Although it would be possible to trail translation and rotation along all three axes, preliminary tests revealed that allowing the user to lift the object off the table caused it to move away from the tracked area, causing tracking breaks.

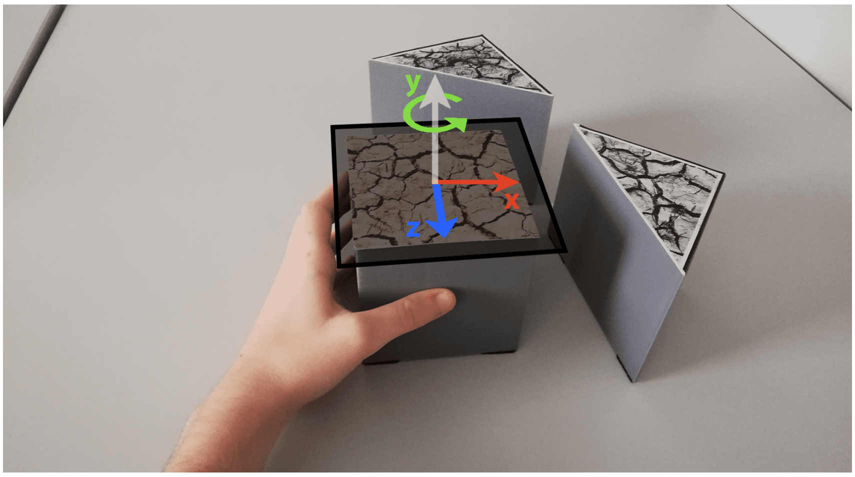


Figure 3.4: Each tangible object was marked with a unique target image to be tracked by a marker-based application. The user could move objects along the x-axis and z-axis and rotate them around the y-axis.

3.6 Task Design

Knowing the system requirements and, now with the conclusions obtained from the preliminary prototype, two games were designed: Target Game and Puzzle Game.

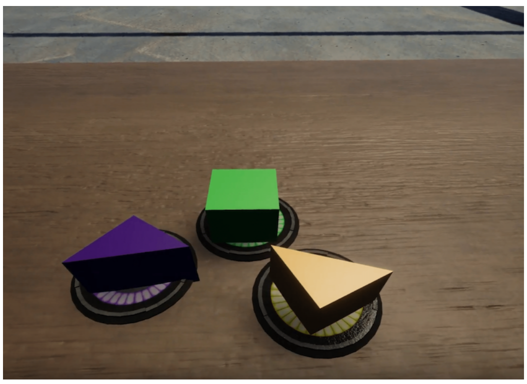
These two games were the tasks performed by users inside the VR Lab. To address the four proposed morphing scenarios, the games were displayed on the time or space conditions that each scenario proposes to investigate. The two games are presented below, as well as the scenarios where they are applied and why they are shown to be appropriate tasks.

Target Game

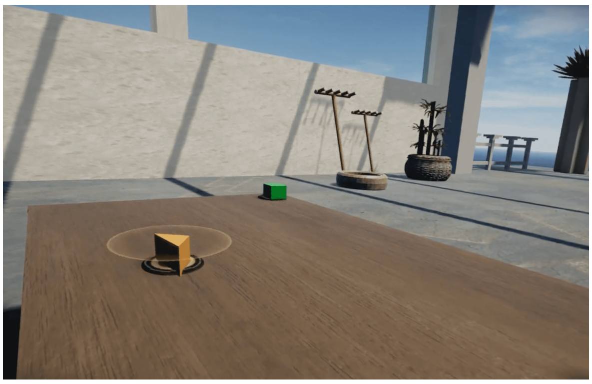
In the Target Game (Figure 3.5), three targets appear scattered around the table. As well as the objects, the targets have different colours. The user's goal is to place each object under the target of the same colour. When all three objects are on the correct target, the targets disappear and reappear in other positions. This rearrangement happens four times to cover different spots on the table. Thus, the game is accomplished after the correct match of twelve targets.

This game was designed to be less mentally challenging, being ideal for assessing performance rather than dexterity. By placing the targets in different positions of the game area, the user is invited to navigate through the virtual space augmented by the geometries under study (Euclidean and hyperbolic). It is possible to analyse the comfort of the users playing the game under the different morphing functions and subsequently compare the performance in each. Thus, this game is suitable to be applied in the *Spatial Function Scenario* and consequently answer research question **Q1**.

As a baseline in the comparison, we will have a condition where the playing area is not enlarged. That is, it recreates the normal real-world conditions, familiar to the user. Under the baseline condition, the virtual playing area and the physical playing area have the same size; hence, only part of the virtual table is used, as shown in Figure 3.5a. In Figure 3.5b, the morphing function used already allows the use of the whole virtual table area.



(a) Playing area under the baseline condition.



(b) Augmented playing area.

Figure 3.5: Target Game - the game goal is to place the objects under the target of the same colour.

Puzzle Game

In the Puzzle Game, the user uses tangible objects to assemble the puzzles displayed in front of him/her. In this context, a puzzle is a construction composed of a square and two triangles, with different arrangements and orientations. The user must use the tangible objects to recreate the displayed figure, as illustrated in Figure 3.6. The game ends after the user successfully completes four puzzles, displayed individually, one after the other.

Although this game relies on basic object manipulation (translation and rotation), it requires more mental effort than the Target Game. To construct a puzzle, the user must think about the spatial relationship between the pieces and tends to move more than one object simultaneously. Placing the objects with the correct rotations also requires more detailed movements, which can become more difficult in the presence of latency. Thus, applying this game to the *Time Morphing Scenario* is fitting to address research question **Q2** on the impact of visual delay on tangible VEs.

The Puzzle Game is also appropriate to study the *Object Size Scenario*, which addresses research question **Q3**. By changing the size of the objects, we aim to explore whether the performance in assembling the puzzle is maintained or whether it affects the user's spatial perception.

Finally, the game is also applied in the *Hand Model Scenario*, associated with the question **Q4**, which intends to study if the virtual hands display helps the user arrange the objects more easily.

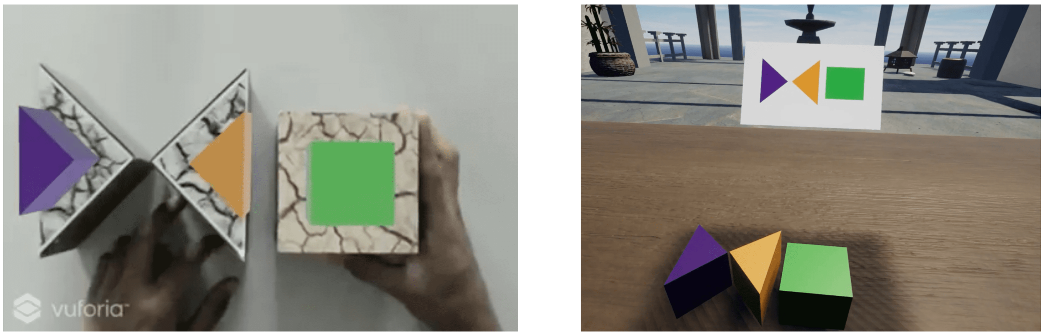


Figure 3.6: Puzzle Game - The image on the right is the user's view of the virtual world. The tracking application captures the image on the left while tracking the objects handled by the user.

Post-task Questions

More than evaluating users' performance, we are interested in knowing their opinion about the different spatiotemporal tasks. A morphing condition may prove suitable for performance improvements; however, it may not suit user preference or vice versa.

The two games presented, without any distortion of space or time, constitute simple tasks. We are interested in knowing if, under the spatiotemporal conditions, the ease of the task is affected from the user's perspective. Additionally, even if the ease is identical

(a) Select the answer by tapping. (b) Answer aloud.

Figure 3.7: Two approach to post-task questions within the VE.

for different conditions, we want to know which condition the user prefers and which one is less preferable.

This information could be collected at the end of the experiment by asking the user to fill a questionnaire. However, at the end of the session, the participant may no longer remember the scenarios they performed at the beginning, making their answers potentially unobjective. To avoid this subjectivity, the questionnaires could be filled in after each scenario. On the other hand, making the user transit between the real and virtual worlds would cause many breaks in presence. Adopting the recommendation of Putze et al. [39], discussed in the state-of-the-art (section 2.1.1), we chose to display the questions after each scenario, but inside the VE, to keep the user engaged in the virtual world. Thus, depending on what we are supposed to investigate in each scenario, questions can be displayed after each scenario or between tasks to ask the user about how easy they felt performing each task, their preference and their level of discomfort.

In the preliminary prototype, questionnaires were designed so that users could select their answers from the options that appeared on the table. Figure 3.7a illustrates a first implementation. However, preliminary testing revealed that this method did not encourage users to justify their answers. In user studies, these complementary justifications proved to be helpful to follow the user's reasoning during the experience and understand if the answer given meets the reported comments. Therefore, we have chosen to design these questions so that the user answers aloud and feels more comfortable justifying their choice whenever they think appropriate. Figure 3.7b shows one of the questions used in the final prototype, which will be discussed in more detail in the implementation chapter (section 4.2.4).

3.7 Summary

After this chapter, the research questions were clarified based on related works raised in the state of the art. Each research question motivated the creation of a spatial or temporal morphing scenario, which will be tested in a virtual room designed to study different spatiotemporal conditions - the VR Lab.

Once the system requirements and the case study were established, the experimental setup adopted to carry out the user study was set. The different morphing scenarios should be presented to the user in simple tasks that would not bias the results for complexity reasons. After testing the preliminary prototype, it was possible to extract valuable outcomes for designing two games suitable for studying each scenario: Target Game and Puzzle Game. Additionally, an approach to inquiring the users inside the VE was also designed to prevent breaks in presence.

4

Implementation

After presenting the requirements of the VR Lab system and the design decisions, this chapter exposes the tools adopted in the implementation phase.

Recalling the system architecture described in Figure 3.2, the VR Lab system comprises two applications: the VR Application (VRApp) and the Object Tracking Application (OTApp). The VRApp is responsible for simulating the morphing scenarios and rendering the virtual world displayed to the user. OTApp is accountable for tracking tangible objects.

This chapter delves into the implementation of the two applications, as well as the communication between them. Each morphing scenario is presented individually, detailing the conditions studied in each and how they were implemented.

4.1 Technologies

The experimental environment requires both hardware and software components. This section discusses the devices and main tools used to develop the VR scene, the tracking engine and the network layer used to connect the two applications.

Hardware devices

The hardware devices used in the experiment were an HMD, a webcam, and a computer to run the VE. The HMD used was the HTC Vive Cosmos, and the webcam used supports full HD 1080p. A PC with an NVIDIA GeForce RTX 30 Series video card, an Intel® Core™ i7-10750H CPU with 2.60 GHz and 16 GB RAM was used to create and run the VR simulation. Both the HMD and the webcam were connected by cable to the PC.

Software Tools

Unity:[1] The software chosen to implement the system was Unity, a cross-platform game engine and development environment, which provides a base API and feature

[1] Unity: https://unity.com/ - Last accessed 14/11/2021

set compatible for multiple devices, including VR devices. The choice of Unity over other game engines platforms (e.g., Unreal Engine[2]) was due to predominant resources and information available concerning assets in the asset store, documentation, and an active developer community in forums that can help solve problems that arise during implementation.

XR Interaction Toolkit:[3] This package was used for creating the VR experience since it provides a framework that makes 3D and UI interactions available from Unity input events. The toolkit offers interactors and interactables that allow users to interact with the virtual world through VR devices.

Vive Hand Tracking SDK:[4] The experiment was intended to develop an environment where user interaction with the virtual world did not require handheld controllers. Therefore, this SDK allowed hand tracking using the HTC Vive Cosmos' built-in cameras.

Vuforia Engine SDK:[5] Vuforia Engine is a platform widely used for AR development that uses computer vision technology to recognize and track planar images and 3D objects in real-time. Vuforia was used to implement the tangible objects tracking application to accurately gather the position and orientation of the objects.

Mirror Networking:[6] The tracking application collects the position and orientation of tangible objects in real-time. This data is sent over a network to the application that performs the space and time morphing and renders the virtual world. Mirror is a high-level Networking API for Unity that simplified the communication between the two applications. Instead of having one code base for the server and one for the client, Mirror simply uses the same code for both.

SketchUp:[7] SketchUp is a software for drawing 3D models. It was used to draw the models of the tangible objects used in the Unity scene.

4.2 VR Lab Scene

This section describes the VR Application (VRApp) responsible for rendering the VR scene presented to the user through the HMD. As introduced in the case study (section 3.3), the VE should provide a large and comfortable space capable of distracting the user from the real environment while performing the proposed tasks. Since Tangram, an Asian jigsaw puzzle, inspired the preliminary prototype, the virtual world was designed to take the user to a relaxing open space in an oriental country. The scene was then decorated with objects that addressed the chosen theme. To also immerse the auditory sense, the user could hear birds and running water sounds as background audio.

Although the user can walk through the developed space, the play area is restricted to the table, where all tasks occur. The virtual table is about three times larger than the

[2] Unreal Engine: https://www.unrealengine.com/ - Last accessed 14/11/2021

[3] XR Interaction Toolkit: https://docs.unity3d.com/Packages/com.unity.xr.interaction.toolkit@1.0/manual/ - Last accessed 14/11/2021

[4] Vive Hand Tracking SDK Overview: https://hub.vive.com/storage/tracking/overview/ - Last accessed

Figure 4.1: Overview of the Unity scene implemented to create the VE where the user performs the tasks.

physical play area (60×40 cm), to which the user is limited in the real world. This size was established after conducting initial tests that revealed that using a virtual table two times larger than the physical area did not differ significantly from the original size. However, if the virtual table was more than three times larger than the physical area, the user had difficulty seeing objects further away, on the edges of the table.

The virtual scene was implemented from scratch. Except for the virtual representation of the tangible objects modelled in SketchUp, most virtual objects were obtained from Unity's Asset Store. Figure 4.1 presents an overview of the virtual scene developed, and Figure 4.2 shows the user during the experiment and her first-person perspective of the virtual world.

14/11/2021

[5]Vuforia Engine: https://developer.vuforia.com/ - Last accessed 14/11/2021

[6]Mirror Networking: https://mirror-networking.com/ - Last accessed 14/11/2021

[7]SketchUp: https://www.sketchup.com/ - Last accessed 14/11/2021

Figure 4.2: The first-person perspective of the virtual world seen by the user during the experience.

4.2.1 Target Game

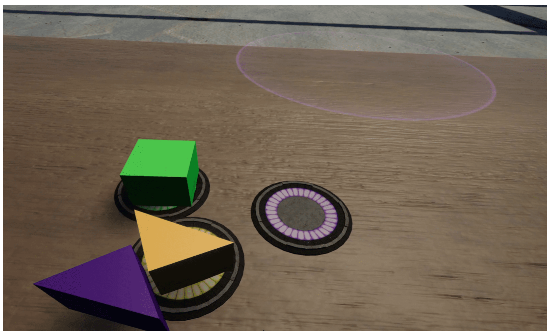
Three targets of different colors were used on the Target Game. The targets vertically emit circles of their respective color to indicate to the user that they have not yet been validated (Figure 4.3). A target is validated when it matches an object of the same color. This validation was implemented based on colliders and tags. In Unity, a collider[8] is a component that defines the shape of an object for the purpose of physical collisions. A tag[9] is a reference word that can be assigned to one or several objects in the virtual scene. When a collision occurs between an object and a target, an event is triggered. This event checks whether the two colliders' tag matches – e.g. if the two tags are "Orange", the target is validated.

When a target is validated as correct, the user can hear a validation sound, and the target stops emitting circles. When all three targets are validated, they disappear and reappear in other positions. This rearrangement happens four times so that the targets can be distributed over different positions on the table. Figure 4.4 shows the different positions that the targets can take. Thus, the user completes the game after the correct match of 12 targets. Initially, it was envisioned to test more positions, but preliminary testing revealed that more than 12 positions would make the experience long and fatiguing.

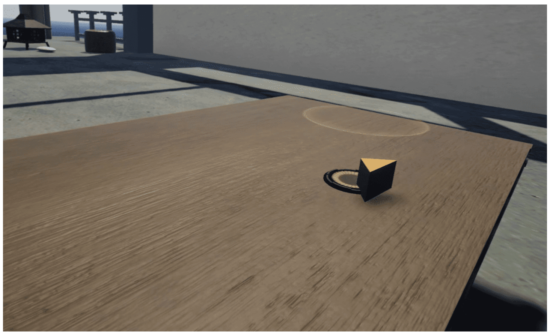
This game is used to study the *Space Function Scenario* (section 4.4.1), which each user performs under four different conditions (F0, F1, F2 and F3). The assignment of each target's positions was randomised and maintained across the four functions tested to ensure equal conditions.

[8] Collider Unity Documentation: https://docs.unity3d.com/ScriptReference/Collider.html - Last accessed 21/11/2021

[9] Tags Unity Documentation: https://docs.unity3d.com/Manual/Tags.html - Last accessed 21/11/2021



(a) Playing area under the baseline condition.



(b) Augmented playing area.

Figure 4.3: Targets that have not yet been validated emit circles vertically. Figure 4.3a shows the targets under the baseline condition; Figure 4.3b shows the targets distributed over the augmented area.

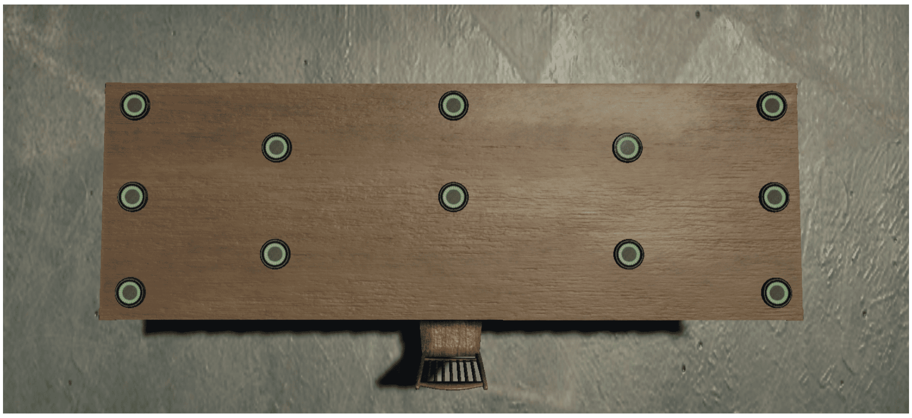


Figure 4.4: The different positions that targets can take during the game.

4.2.2 Puzzle Game

In this game, users must assemble puzzles with the three tangible objects. A puzzle game is completed after the user correctly constructed four figures. It was envisioned to require the assembly of six figures, but preliminary tests showed that this number would make the experience long and tiring.

Thirty puzzles with similar difficulty were designed and presented to users in random order. Figure 4.5 shows three of these puzzles.

Initially, a validation algorithm was implemented to verify if the puzzle assembled by the user matched the puzzle of the presented figure. For each puzzle, conditions were established under which a puzzle could be considered well assembled. These conditions included each object's rotation and the minimum and maximum distances an object should be from the other two. In testing this algorithm, we realized that it was poorly tolerable to minor tracking flaws. If, for example, users placed their hand over the tangible object marker during assembly, Vuforia could incorrectly determine the rotation, leading to false-positive validations.

Although improvements to the algorithm were tried, we opted for manual validation made by the researcher to ensure accuracy. The researcher only skips to the next

Figure 4.5: Three examples of the puzzles presented to users.

puzzle, through the computer-accessible UI (section 4.2.3), when the current one is well constructed. The validation process is transparent to users, who believe that the verification is done by the system as long as the puzzle is mounted in the shaded rectangular area. Also, the shaded area proved to be an effective method of preventing the user from dragging the physical objects outside the play area captured by the webcam.

4.2.3 Researcher UI

The researcher UI was initially implemented to facilitate debugging in the testing stage; however, it proved helpful in the user study stage, enabling the researcher to interact with the system without using the handheld controllers. The researcher could easily manage the scenarios displayed using the computer's mouse through a simple UI, as shown in Figure 4.6. The control panel in the upper right corner was used in the implementation phase to test the different conditions. The Mirror extension uses the buttons on the left corner to establish the network connection with the OTApp at the beginning of the session. The network layer will be discussed later in section 4.11.

For the user studies, it was decided to present the different spatiotemporal conditions in a Latin-square order, as discussed further in section 5.1.1. A Latin-square algorithm was implemented to automatically update the order in which the conditions are presented with each new participant. The researcher just has to click on the "Next Task"button to proceed to the next morphing condition. Figure 4.7 shows the view of the researcher through the PC display. The buttons in the bottom right corner allow the researcher to

Figure 4.6: Control panel used to test the different spatiotemporal conditions during the implementation stage.

Figure 4.7: Researcher UI used via PC.

move tasks forward and backwards. In the bottom left corner, the researcher can record the answers given by participants to questions posed during the session. In the upper right corner, the researcher can check which scenario is being performed.

The interface was implemented using the "Immediate Mode"GUI[10] system, a tool accessible in Unity and primarily intended for programmers.

4.2.4 Questionnaires Embedded in the VE

During the experiment, users play the two games under different spatiotemporal conditions. After each condition or scenario, users can be asked about how easy they found the task (subjective ease), their level of discomfort, or their preference between certain conditions.

To minimize breaks in presence, it was decided to implement the questions embedded in VE. Figure 4.8 shows the three questions that can arise during the experiment. In section 5.1.1, it is specified under what circumstances each one is displayed.

On the subjective ease question (Figure 4.8a), users are asked to rate, on a 7-point Likert scale (1=strongly disagree and 7=strongly agree), the statement "I found this task easy.". On the discomfort question (Figure 4.8b), users have to rate the statement "I experience any symptoms of discomfort (e.g., fatigue, nausea)"on the previously mentioned 7-point Likert scale. In the preference questions, the users have to order the illustrated conditions according to their preference (from most to least preferable). Figure 4.8c, shows the conditions in the *Hand Model Scenario*, but the equivalent question can be asked in the *Object Size Scenario*.

[10]Immediate Mode GUI (IMGUI): https://docs.unity3d.com/Manual/GUIScriptingGuide.html - Last accessed 22/11/2021

(a) Subjective ease question. (b) Discomfort question. (c) Preference question.

Figure 4.8: During the experiment, questions posed to users are embedded in the VE and can be of the three types shown.

Users answer the questions aloud to easily justify them whenever they want or find it necessary. The researcher can record the answers in real-time via the researcher UI. These answers are saved to generate a report at the end of the experiment.

4.3 Tangible Interaction

The VRApp is responsible for rendering the virtual world along with the morphing scenarios, as presented in the previous session. In turn, OTApp is accountable for tracking tangible objects. This section presents the implementation of OTApp and how it communicates with VRApp.

4.3.1 Object Tracking

During the initial research on tangible VR solutions (section 2.1.5), it was possible to verify that most approaches required additional hardware and circuits to represent the tangible objects into the virtual world. Furthermore, some solutions are strongly oriented to specific objects with previously known shapes and dimensions, making the system inflexible to incorporate different objects.

The approach that showed to be more suitable for the VR Lab system was a marker-based approach, typically used in AR systems. These markers are used to track the position and orientation of each object. Thus, to the standard VR setup, it was only necessary to add a webcam, which makes the system scalable to track any tangible object, as long as each object is previously marked with a unique target image.

The case study involves three tangible objects: a cube and two triangular prisms. The tangible objects were 3D printed and had purposely simple shapes to avoid tracking errors. Their sizes were kept as minimal as possible to allow one-handed interaction but large enough to be tracked seamlessly by the webcam. Each object has a 10 cm edge with a target image that fills its entire upper face. Since the user does not have to rotate the

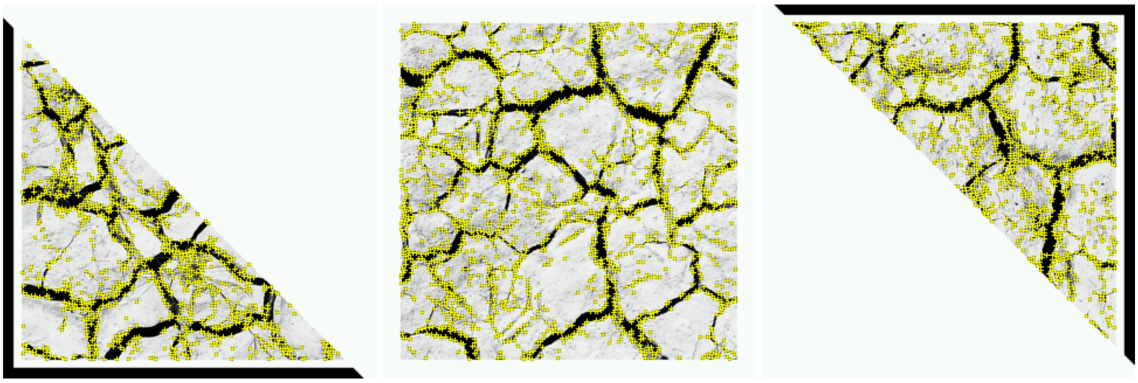


Figure 4.9: Target images chosen for the tangible objects. The yellow crosses indicate the key points that Vuforia tracks to determine the position and orientation of objects.

object, the upper face always faces the webcam, and it was not necessary to mark any other face.

The OTApp relies on the Vuforia SDK, which uses computer vision technology to track markers. Briefly, the Vuforia library[11] uses Natural Feature Tracking (NFT) algorithms with an approach similar to Scale Invariant Feature Transform (SIFT) to detect feature key points and determine the scale of the marker.

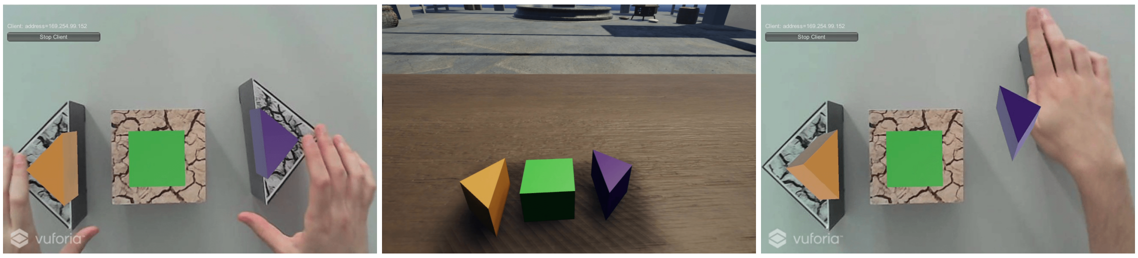
The target images chosen for each object followed the best practices recommended by Vuforia[12], which advise markers rich in features, i.e., images with sharp, spiked, chiselled details. Thus, the images chosen are rich in detail and contrast, with bright and dark regions and well-lit areas, as shown in Figure 4.9. The yellow crosses indicate the key points that Vuforia will track to calculate the object's position and orientation. The more key points, the less likely tracking failures will occur.

Figure 4.10a and Figure 4.10c show two images captured by Vuforia during object tracking; Figure 4.10b corresponds to the respective user's view inside the VE. To facilitate the debugging, the virtual objects corresponding to each marker appear over it to indicate that they are correctly detected.

At the beginning of the experiment, users were asked to handle the objects without hiding the top marker. Even so, the size of the markers allows that even if users partially cover the mark with their hands - and therefore hide some key points - the tracking is not affected since the visibility of the remaining key points can guarantee the correct position and orientation calculation. If the user covers a large part of the image target, as it happens in Figure 4.10c, Vuforia loses the tracking for that object. Consequently, in the VE, the user sees the object at the last position tracked. Initially, in cases of tracking breaks, we would make the virtual object disappear from the table. However,

[11] Vuforia Fusion: https://library.vuforia.com/articles/Training/vuforia-fusion-article.html - Last accessed 15/11/2021

[12] Best Practices for Image-Based Targets: https://library.vuforia.com/features/images/image-targets/best-practices-for-designing-and-developing-image-based-targets.html - Last accessed 15/11/2021



(a) All three markers are visible. (b) User view inside the EV. (c) The right marker is hidden.

Figure 4.10: Tangible objects tracking performed by Vuforia.

preliminary tests concluded that this approach would confuse users, as they showed difficulty relocating the object on the physical table. Moreover, to avoid mishandling of objects, the experiment starts with a training phase for users to adapt to the correct handling.

4.3.2 Networking

Once the position and orientation of the three objects are known, it is necessary to pass this data to the VRApp, so it can be used to map the virtual objects according to the spatiotemporal conditions under study in each morphing scenario. For this purpose, a networking layer was used to establish the communication between the VRApp and the OTApp.

Since the implementation of low-level networking features falls outside the main scope of this dissertation, the networking API Mirror was used to streamline the implementation in the networking layer. Figure 4.11 schematizes the communication between the two applications. VRApp acts as the server, and OTApp acts as the client. OTApp continually updates the position and orientation of each object. Through call functions of the Mirror API, this information is automatically updated on the server-side and processed in the morphing module, which has as output the warped position according to the spatiotemporal morphing scenario under study. The respective virtual object's transform (position and rotation) is then updated according to the post-morphing data.

The decoupling of the two applications makes it possible to execute them on separate

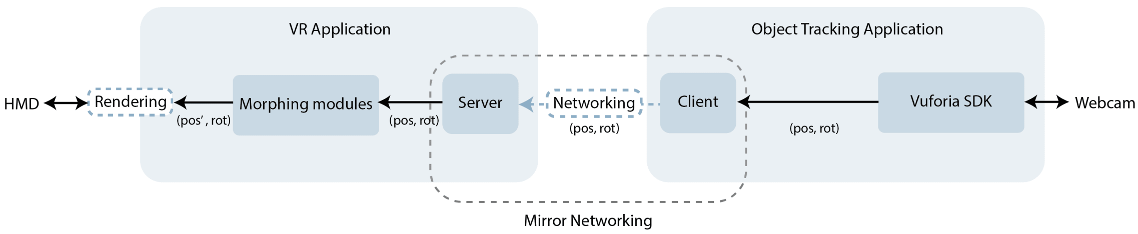


Figure 4.11: Schematic of the networking between VR Application and Object Tracking Application.

computers. However, since the *Time Morphing Scenario* requires simulating different levels of delay, we opted to run both applications on the same machine for local networking to avoid additional delay beyond the intended.

4.3.3 Calibration

It was necessary to include a calibration phase to match the physical and virtual play areas to ensure the virtual objects are correctly mapped onto the virtual table. This calibration relies on a function that translates the real-world coordinates collected in the OTApp, into virtual world coordinates used in the VRApp. This step is only required when the playing area changes (e.g., when the webcam is relocated) since the calibration settings can be saved and retrieved in subsequent uses.

Since the user only moves the objects along the x and z axes (as explained in section 3.5), we assume that a point in the real world is composed of two coordinates, $r = (x_r, z_r)$, and has a virtual counterpart, $v = (x_v, z_v)$. Knowing two points in the real world, r_1 and r_2, and their respective points in the virtual world, v_1 and v_2, it becomes possible to map any point from the real world onto its representation in the virtual world through linear interpolation present by the function f_0,

$$f_0(x_r) = x_v = mx_r + b \tag{4.1}$$

$$m = \frac{x_{v_2} - x_{v_1}}{x_{r_2} - x_{r_1}}, \; b = \frac{x_{r_2}x_{v_1} - x_{r_1}x_{v_2}}{x_{r_2} - x_{r_1}} \tag{4.2}$$

We define m and b as the slope and displacement required to match the real and virtual world.

Considering that both the real and virtual axes are aligned, the equation is applied individually to each coordinate of a point. Function f_0 exemplifies the application only to the x-coordinate to simplify writing the equation; the calculus is identical for the z-coordinate. Note that no calibration function is required for the object orientation. The orientation around the y-axis is collected in the OTApp application and preserved in the VRApp virtual world.

The calibration method was implemented to provide an accurate calibration independent of the gaming area used. The two real-world points (r_1 and r_2) are determined through the initial position of two tangible objects; the two corresponding points in the virtual world (v_1 and v_2) are accurately indicated through hand tracking functionality.

Figure 4.12 illustrates the calibration steps. On the OTApp side (Step 1), the two triangular prisms were used to determine the real-world points. The process that will be explained next would be exactly the same if the cube was selected instead of one of the prisms. The points r_1 and r_2 correspond to the initial position of the two tangible objects. These positions can be arbitrary, but preferably the two objects must be positioned

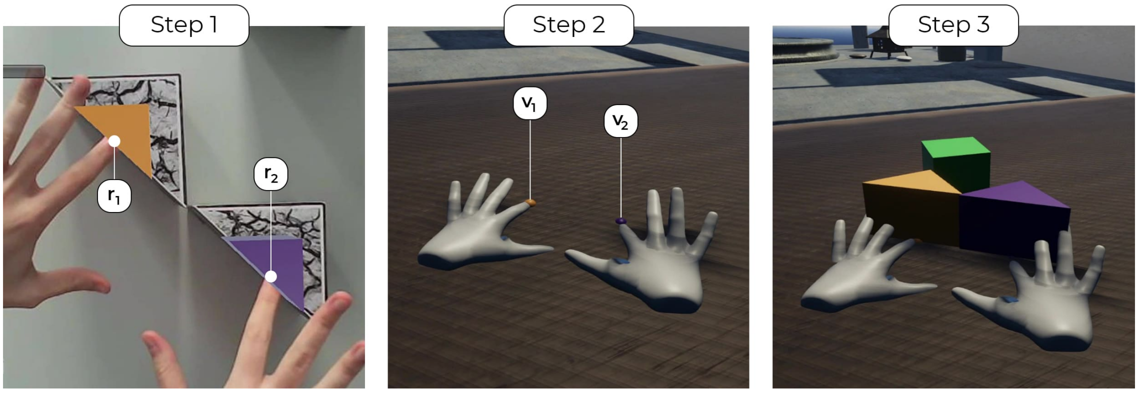


Figure 4.12: Calibration steps to map the tangible objects onto the virtual table; r_1 and r_2 are two arbitrary points in the real world, and v_1 and v_2 are the respective points in the virtual world.

diagonally to each other to perceive the scale of the space. Placing the two objects side by side, vertically or horizontally, can lead to one of the coordinates (x or z) not being well-calibrated.

On the VRApp side (Step 2), the virtual points are accurately determined by the hand recognition system provided by the Vive HMD (further explained in section 4.4.3). The points v_1 and v_2 are given by the collision point between the index finger node and the virtual table. Small spheres identify the collision points. Once the index fingers determine v_1 and v_2, we can map real points into virtual points, and the physical objects' movements are reliably reflected in the virtual play area (Step 3). In other words, this calibration process is sufficient to map the physical objects onto the virtual world without any spatial distortion.

The *Spatial Function Scenario* (section 4.4.1) requires an additional step because the tasks in this scenario involve increasing the virtual play area. In practice, it means that the extremes of the physical play area are stretched to the extremes of the virtual table. This space augmentation can also be simulated by linear interpolation applying a function identical to Equation 4.1. Still, this time we want the ends of the area tracked by the webcam (R_1 and R_2) to be mapped onto the ends of the virtual table (V_1 and V_2) to ensure that the entire physical area covers the whole virtual table proportionally. As illustrated in Figure 4.13, R_1 and R_2 are determined identically as r_1 and r_2; V_1 and V_2 are easily known within the virtual scene.

4.4 Space Morphing

With space morphing, we refer to any spatial distortion applied in the VE; it may include changing the space geometry or changing properties of the virtual objects, such as color, size or shape.

This section is intended to present the three space morphing scenarios that address the research questions (section 1.2) Q1, Q3 and Q4: *Spatial Function Scenario*, *Object Size*

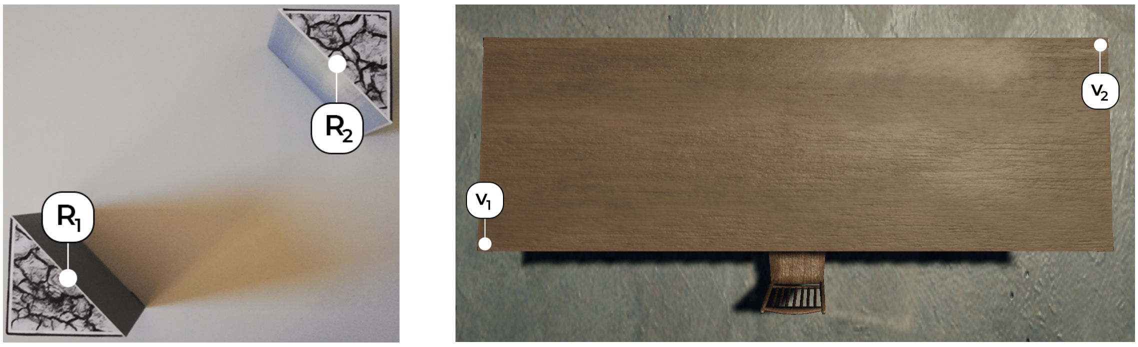


Figure 4.13: To augmented the virtual area, the two points of the real world (R1 and R2) and the two points of the virtual world (V1 and V2) must coincide with the extremes of the real and virtual playing area, respectively.

Scenario and *Hand Model Scenario*, respectively.

4.4.1 Spatial Function Scenario

This morphing scenario takes advantage of VR capabilities to create the illusion of a larger play area. Although the user is still restricted to the same physical area, the virtual play area is about three times larger. The illusion of a larger space is created by the mathematical function used to map the objects onto the virtual table. Instead of mapping the objects within a virtual area identical to the physical area, the function stretches this mapping to a larger virtual area, as illustrated in Figure 4.13. Three functions were studied to augment the virtual space: one linear function (F1) and two hyperbolic functions (F2 and F3).

The study of these three functions addresses the research question Q1, which aims to compare the adaptability of users to Euclidean and hyperbolic spaces. The baseline condition and the three morphing functions implementation are presented below.

F0 - Baseline

As a baseline, a condition of this scenario has no spatial distortion in the mapping between the real and the virtual objects. In this case, the position of the virtual objects is determined by the function f_0, described in Equation 4.1. Under this condition, the real and virtual play areas have the same dimension, and objects move equally in both spaces. Therefore, there is no space augmentation, and only part of the virtual table is used, as illustrated by the white grid in Figure 4.14.

F1 - Linear Function

The function f_1 was used to increase the virtual play area linearly,

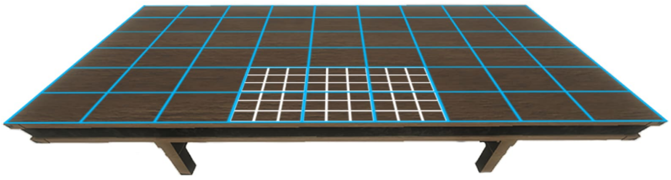


Figure 4.14: The white grid represents the play area mapped by the linear function F0; the blue grid represents the play area mapped by the linear function F1.

$$f_1(x_r) = x_v = mx_r + b \tag{4.3}$$

$$m = \frac{x_{V_2} - x_{V_1}}{x_{R_2} - x_{R_1}}, \; b = \frac{x_{R_2}x_{V_1} - x_{R_1}x_{V_2}}{x_{R_2} - x_{R_1}} \tag{4.4}$$

Functions f_1 and f_0 are similar, except that in f_1, the slope m and the intercept b are calculated using the extreme positions of the physical area (R_1 and R_2) and the virtual area ($V_1$and V_2), known in the calibration phase (section 4.3.3). Under these conditions, the play area is stretched to cover the entire virtual table, as illustrated by the blue grid in Figure 4.14. The user is still facing a Euclidean space, but his/her movements are amplified to create the perception of a larger space.

F2 - Hyperbolic Tangent

In this approach, the mapping is essentially determined by the hyperbolic tangent function, *tanh*,

$$tanh(x) = \frac{e^{2x} - 1}{e^{2x} + 1}, \qquad tanh(x) \in [-1, 1] \tag{4.5}$$

Function *tanh* makes the space wider in the center of the playing area and tighter at the ends, as suggested by Figure 4.15. The displacement of the physical object translates into an extremely large movement of the virtual object when performed in the center of the table. However, if the same action takes place at the table ends, the virtual movement will not be as large. Under these conditions, the user must be more precise to place objects into targets in the center since a minimal movement quickly brings the object to

Figure 4.15: Hyperbolic Tangent (F2)

the edges. In contrast, the user must make a broader movement to drag the objects from the extremes to the center.

Given the characteristics of the *tanh* function, additional steps were taken in the implementation phase to ensure the correct mapping of real coordinates into virtual coordinates. The hyperbolic tangent function, *tanh*, tends towards -1 for values less than $-a$ and tends towards 1 for values greater than a. Thus, to avoid infinite values, before using the *tanh* function, a linear cut-off function, f_g, is applied to maps the real coordinate, x_r, into a value, x_g, within a finite range,

$$x_g = f_g(x_r), \qquad x_g \in [-a, a] \quad and \quad a \in \mathbb{R} \tag{4.6}$$

The result of f_g is subsequently applied to the function *tanh*,

$$x_h = tanh(f_g(x_r)), \qquad x_h \in [-1, 1] \tag{4.7}$$

This way, we ensure that the function *tanh* only receives finite values. Finally, a linear function, f_j, is used to convert the value x_h into a virtual world coordinate, x_v, within the boundaries of the virtual table.

$$f_2(x_r) = x_v = f_j(tanh(f_g(x_r))), \qquad x_v \in \left[x_{V_1}, x_{V_2}\right] \tag{4.8}$$

F3 - Inverse Hyperbolic Tangent

Under this condition, the coordinates of the virtual objects are determined by the inverse hyperbolic tangent, *arctanh*,

$$arctanh(x) = \frac{1}{2} ln\left(\frac{1+x}{1-x}\right), \qquad arctanh(x) \in [-\infty, +\infty] \tag{4.9}$$

which causes the inverse behaviour described in F2. As shown in Figure 4.16, the space is modified to become narrower in the center of the table and wider at the ends. These conditions require the user to make meticulous movements to place objects into targets near the table ends since a more abrupt movement will take the object off the table. In comparison, moving objects in the center of the play area allows broad movements.

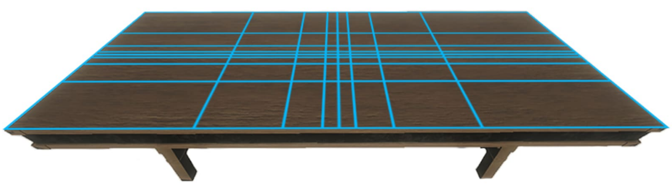


Figure 4.16: Inverse Hyperbolic Tangent (F3)

As with condition F2, additional steps were required in the implementation phase. Since the inverse hyperbolic tangent function, *arctanh*, tends to infinite values when x is close to -1 and 1, a linear function, f_k, sets the range of [-0.97; 0.97] to avoid infinite values.

$$x_k = f_k(x_r), \qquad x_k \in [-0.97; 0.97] \tag{4.10}$$

The result of f_k is subsequently applied to the function *arctanh*,

$$x_h = arctanh(f_k(x_r)), \qquad x_h \in [arctanh(-0.97); arctanh(0.97)] \tag{4.11}$$

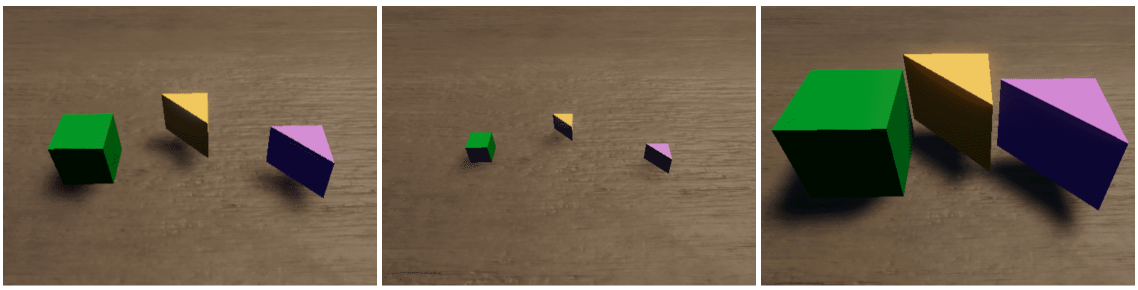
Lastly, a linear function, f_l, is applied to convert the result x_h into a coordinate belonging to the playing area of the virtual table, x_v.

$$f_3(x_r) = x_v = f_l(arctanh(f_k(x_r))), \qquad x_v \in \left[x_{V_1}, x_{V_2}\right] \tag{4.12}$$

4.4.2 Object Size Scenario

This scenario aims to investigate the influence of the virtual object size in the performance task. Figure 4.17 shows the three sizes studied: small, normal and large. The normal size is equivalent to 10 cm of edge, which is the size of the physical objects. The small and large sizes are respectively half and twice the normal size.

The normal size of the virtual objects was guaranteed in the modeling phase. The three objects were modeled in SketchUp software, which allows drawing 3D models with the desired measurements. The small and large sizes were later implemented in Unity by changing the scale of the objects to 0.5 and 2 units, respectively.

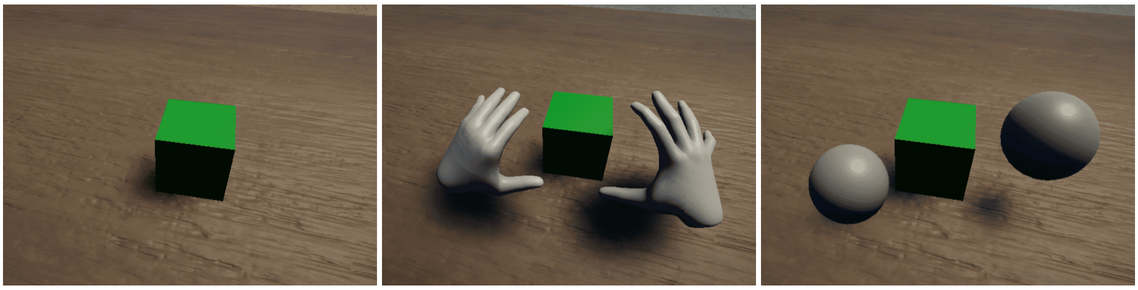


(a) Normal (S0). (b) Small (S1). (c) Large (S2).

Figure 4.17: The three sizes of the virtual objects studied.

4.4.3 Hand Model Scenario

Figure 4.18 shows the three conditions studied: no hands, human hands, and abstract hands. The baseline from this morphing scenario is performing the task without any hand representation.



(a) No hands (H0). (b) Human model (H1). (c) Abstract model (H2).

Figure 4.18: The three hand models studied.

The human hand model was implemented using the Vive Hand Tracking SDK. This tool uses the built-in cameras of the HTC Vive Cosmos headset to track the hands. The engine supports left- and right-hand tracking with inner level positional tracking, consisting of 21 points: four points per finger and one point at the wrist. The hand model is dynamically rendered through the position of the 21 points. The abstract model reuses the exact mechanism for tracking hands, but instead of hands, a sphere model is used. This abstract model serves to investigate whether a more minimalist model of the hand can act as a reference point for the user to situate their hands in virtual space.

Preliminary tests revealed that the Vive Hand Tracking SDK provides satisfactory hand detection when all fingers are clearly visible to the HMD's built-in cameras. However, when the user handles the tangible objects, some fingers might be hidden, resulting in occasional bizarre hand representations, as illustrated in Figure 4.19.

Faced with this limitation, we experimented with different conditions to understand which ones prevented tracking errors. Listed below are the conclusions we drew from the main conditions tested.

Marker-based hand tracking: As an alternative to Vive's hand tracking, a marker-based mechanism was implemented. The user's hands are marked with target images to be tracked by OTApp, in the same way as tangible objects (section 4.3.1). Figure 4.20

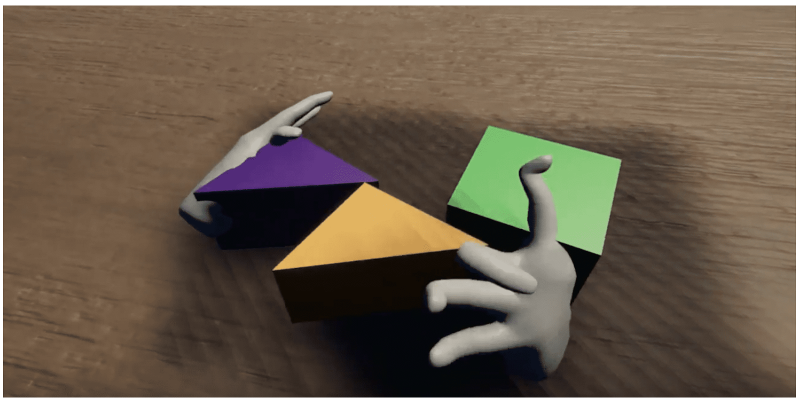


Figure 4.19: Hand model rendering error due to occlusion of fingers when grasping objects.

(a) Markers placed on the user's hands with rubber bands.

(b) Hand model that does not vary posture.

(c) A circle indicates the hand position on the table.

Figure 4.20: Marker-based hand tracking method. Figures 4.20b and 4.20c show the two rigid models tested in this approach.

shows the two static hand models tested. The human hand model (Figure 4.20b) was used, but the hand always presented the same posture (i.e., orientation, finger position, height relative to the table), only varying its position in the x and z axes. Since this approach could not accurately map the distance between the hand and the table, it was tested to represent a simple white circle (Figure 4.20c) on the table that locates only the hand's position in the playing area. None of the models offered a natural and comfortable interaction; users had to maintain a hand position that allowed the markers to always face the webcam; it was not possible to realize how far the hands were from the table due to the static model always being at the same distance from the virtual table. Furthermore, this method degraded the initial motivation of a VE where users could interact with objects in the same way as in the real world, without having devices or markers on their hands.

Lowering the virtual table's height: Lowering the virtual table's height instinctively lead users to tilt their head down, creating a better viewing angle to the headset's built-in cameras detect fingers. This approach proved to be uncomfortable for users. With the head tilted, the weight of the HMD led to users complaining of neck pain after a few minutes.

Increase the vertical distance between the HMD and the physical playing area: We observed that increasing the vertical distance between the HMD and the playing area improved hand tracking. This distance is achieved using a lower physical table or, alternatively, if the user is sitting in a higher chair. In this way, the headset's built-in cameras have a superior view of the hands, allowing better finger tracking.

Neither approach could completely prevent sporadic tracking errors. The method that revealed a better trade-off between tracking accuracy and interaction comfort was to use a higher chair. In this way, the viewing angle of the HMD allowed satisfactory finger tracking while the cervical discomfort was prevented.

4.5 Time Morphing Scenario

Time morphing includes any change applied to the VE that alters the timestamp or natural order of events. For example, these changes might involve delaying the feedback of actions by a few milliseconds or delaying a few seconds and changing the order in which their effects are presented.

In the time morphing scenario studied, the movements of the virtual objects were delayed to analyse the impact that delayed visual feedback can have on user performance in tangible interaction. Thus, the user would only receive visual feedback d ms after moving the physical object, with d being the delay value.

This scenario was performed under the following eight conditions.

D0 – Baseline

The task performed without any additional delay was taken as a baseline.

Dx - Constant delay, $x \in \{20, 50, 100, 200, 500, 1000\}$

Through the survey in section 2.3.2, we pointed out the latency values commonly assessed and arrived at six levels of delay: 20 ms, 50 ms, 100 ms, 200 ms, 500 ms and 1000 ms. Although the value of 1000 ms was not included in any of the experiments surveyed, we decided to include the value in our study to analyse user behaviour at very noticeable delay values.

To simulate the delay of the virtual objects, a data structure was created that acts as a buffer. The positions and rotations of each object at each moment are stored in the buffer. The data stored are used to update the objects' transform (position, rotation) x ms after the task starts, creating the desired motion delay.

This delay of x ms was implemented based on the coroutine system provided by Unity Engine[13]. A coroutine is a function that can suspend its execution until a given instruction finishes. In this case, the updating of the virtual objects is suspended until the initial x ms have passed.

DV - Variable delay

In network-dependent applications, the delay can be non-constant. An additional condition was included to study the user performance in this case, where the delay was variable over time, ranging from 0 ms to 1000 ms. Given two random values, $rand1$ and $rand2$, respectively, between 0-5 seconds and 5-10 seconds, the delay value d was refreshed every $rand1$ seconds, and the delay buffer was cleared every $rand2$ seconds (to simulate moments without delay).

[13] Coroutine Unity Documentation: https://docs.unity3d.com/ScriptReference/Coroutine.html – Last accessed 20/11/2021

This non-constant delay condition was also implemented based on coroutines that continuously updated the delay value d that should be applied to the virtual objects at each point in time.

4.6 Summary

This chapter delved into the details of the VR Lab as an experimental environment to study different conditions of space and time. The system consists of two applications: VR Application (VRApp) and Object Tracking Application (OTApp). This chapter presented each of them.

For the VRApp, it was described the virtual scene and games (Target Game and Puzzle Game) that the user performs inside the virtual world. Embedded questions were also implemented within the VE to question users during different moments of the experience. The researcher interacted with a simple UI through the PC to manage the displayed tasks and register the answers given by the participants.

The OTApp detailed the implementation of the marker-base mechanism used to track the physical objects. The Vuforia SDK was the basis of this application, along with a calibration phase to match the physical and virtual play areas.

Afterwards, the development process of the four morphing scenarios was described: *Spatial Function Scenario*, *Object Size Scenario*, *Hand Model Scenario* and *Time Morphing Scenario*. The conditions studied in each scenario were presented, as well as some challenges and decisions that arose during implementation.

The outcome of the implementation phase was a functional prototype of the VR Lab, ready to be used for user studies and to collect data to inform the research questions.

5

Evaluation and Results

In order to answer the research questions specified in section 1.2 and validate the developed system, a user study was conducted to analyse the participants' behaviour under the different conditions of each morphing scenario.

The first part of this chapter presents the user study design, including the protocol followed, how each morphing scenario was assessed, what data was gathered, and the user questionnaires applied at the end of the experiment.

The second part of this chapter covers the results and analysis. For each morphing scenario, the results obtained under the different conditions performed are presented and discussed. By the end, a section is dedicated to a more general discussion and analysis of the results.

5.1 Evaluation Methods

This section covers the procedure followed in the user study and how each morphing scenario was assessed. For each scenario, the proposed tasks and the data gathered are presented.

The VR lab prototype was developed from scratch. Therefore, we considered it was relevant to apply post-session user questionnaires to evaluate the VR experience and inquire if our implementation did not interfere with the results.

5.1.1 Protocol

Figure 5.1 shows two participants in the experimental environment where the user study took place. All participants performed the experiment in the same room, under the same external conditions.

All participants performed both space and time morphing scenarios under all conditions detailed in section 4.4 and 4.5, respectively. In a nutshell, the experiment comprises three space morphing scenarios and one time morphing scenario, which all together add up to a total of 18 tasks:

- **Space Morphing Scenarios**

Figure 5.1: Users during the user study session.

  - *Spatial Function Scenario*: F0, F1, F2, F3 (4 conditions)
  - *Object Size Scenario*: S0, S1, S2 (3 conditions)
  - *Hand Model Scenario*: H0, H1, H2 (3 conditions)

- **Time Morphing Scenario**
  - D0, D20, D50, D100, D200, D500, D1000, DV (8 conditions)

The order in which the scenarios and their respective conditions were presented to the participants was counterbalanced using the Latin-square assignment by systematically varying the order in a full permutation. Thus, we did not choose a fixed order that could bias the results by learning or fatigue factors affecting the last tasks. To exemplify, the task sequences for the first three participants are shown below. For easier reading, the space morphing tasks are in bold, and the time morphing tasks are underlined.

1st *seq.*: **F0, F1, F2, F3, S0, S1, S2, H0, H1, H2**, D0, D20, D50, D100, D200, D500, D1000, DV
2nd *seq.*: D20, D50, D100, D200, D500, D1000, DV, D0, **S1, S2, S0, H1, H2, H0, F1, F2, F3, F0**
3rd *seq.*: **H2, H0, H1, F2, F3, F0, F1, S2, S0, S1**, D50, D100, D200, D500, D1000, DV, D0, D20

To analyse user adaptability in the different spatiotemporal conditions, we are mainly interested in three factors: completion time, subjective ease of the task, and user preference. By task, we mean a condition of a given scenario.

Completion time, measured in seconds, refers to how long it takes the participant to perform each task. **Subjective ease** concerns how easy the user found the task. This degree of ease is acquired by, after each task, asking the participant to rate the *subjective ease question* in a 7-point Likert Scale (1 = strongly disagree that the task was easy; 7 = strongly agree that the task was easy). Both this question and the following ones are displayed within the VE, as presented in section 4.2.4. This question appears after each *Spatial Function Scenario* and *Time Morphing Scenario* condition. For the *Object Size Scenario* and the *Hand Model Scenario*, we are more interested in analysing the **user's**

Table 5.1: Overview of the game performed and data gathered in each scenario. The data collected are marked with a cross.

Scenario	**Game**		**Data gathered**		
	Target	*Puzzle*	*Completion Time*	*Subjective Ease*	*Preference*
Spatial Function	×		×	×	
Object Size		×	×		×
Hand Model		×	×		×
Time Morphing		×	×	×	

preference. To this end, the *preference question* is displayed, requesting the participant to order the conditions presented from the most to the least preferable. Additionally, to track the user's **level of discomfort**, the *discomfort question* appears three times throughout the experience: at the beginning, after all space morphing scenarios, and after the time morphing scenario. To answer the questions within the VE, the user should answer aloud to feel comfortable to justify their answers whenever they wish. Through its UI, the researcher can register the answers. At the end of the experiment, the system generates a report with the completion times for each task, as well as the answers to the subjective ease, preference, and discomfort questions.

Table 5.1 summarizes the data collected and the game performed in each scenario.

Procedure

The experimental session began by asking the participant to read the informed consent presented in Appendix A. The session started after the participant agreed and signed the consent form.

The researcher started by giving some initial instructions, presenting the three tangible objects the participant would interact with during the session. The participant was instructed on how to handle the objects without covering the target images. Then the participant sat down in front of the table used as the play area and was equipped with the HMD.

The first few minutes of the experiment were reserved for the participant to practice each game once to ensure that he/she was comfortable with the tasks without any morphing added. After the training phase, the researcher explained that the session was composed of several levels. At each level, the participant would have to play one of the two games. The research questions and morphing conditions were not revealed so that the participant's behaviour would not be biased. The researcher only warned the participant that there might be some differences between levels, and a question would appear in which the participant had to rate the ease of the task after each level.

After all tasks were completed, the participant was asked to fill post-experiment questionnaires regarding presence, cybersickness and a demographic questionnaire to gather data about age, gender, sight problems, and VR and video game experience.

5.1.2 Questionnaires

After the experience, participants filled paper post-session questionnaires to evaluate different aspects of the VR experience they just finished.

To validate the implementation of the VR Lab, we are interested in analysing whether the tangible VR experience led the participants to feel immersed and present in the virtual world without triggering symptoms of major discomfort. Through the state-of-the-art survey on evaluation methods in VR (section 2.1.1), we considered it would be appropriate to apply the Simulator Sickness Questionnaire (SSQ) [71], and Igroup Presence Questionnaire (IPQ) [72] to assess cybersickness and presence, respectively.

Finally, participants also filled a characterization questionnaire that collected information about age, gender, education, experience in VR and video games, and sight problems. This information was collected to be later cross-checked with the results obtained in the morphing scenarios to examine whether the characterization factors were related to the participants' better or worse performance.

The questions of the SSQ, IPQ and characterization questionnaires are detailed in Annex I, Annex II and Appendix B, respectively.

5.2 Results and Analysis

The following sections will go over the results and insights obtained. First, the demographic data of the participants who took part in the user study is presented. Next, each morphing scenario has a section dedicated to presenting and discussing the results acquired after processing the gathered data. The results of the post-session questionnaires are also presented. Finally, the research questions are answered in a final discussion section.

5.2.1 Population Characteristics

The population was composed of 28 participants (20 male and 8 female), students from fields of science and engineering: computer science (13), electrical engineering (7), biomedical engineering (5), pharmaceutical science (1), micro and nanotechnology (1), and geological engineering (1). Their demographics are present in Table 5.2 and Figure 5.2.

The participants range in age from 18 to 35 (Figure 5.2a) and have an average height of 1.73 meters (Figure 5.2b). All participants are right-handed (Table 5.2b). The education levels reported were high school (5), bachelor's (20) and master's (3) degrees. Regarding visual impairment (Table 5.2d), 10 participants reported having slight vision problems even with glasses, which could make it difficult to read texts with smaller font sizes. However, only one participant reported having difficulty reading the questions displayed in the VE; the others said they did not experience any significant difficulty.

Regarding VR experience (Figure 5.2c), 16 participants reported never experienced VR before, and only 2 participants use VR every week. Figure 5.2d presents the frequency

Table 5.2: Population demographics tables.

(a) Participants Gender.

Gender	Participants(#)
Male	20
Female	8

(b) Participants Dominant Hand

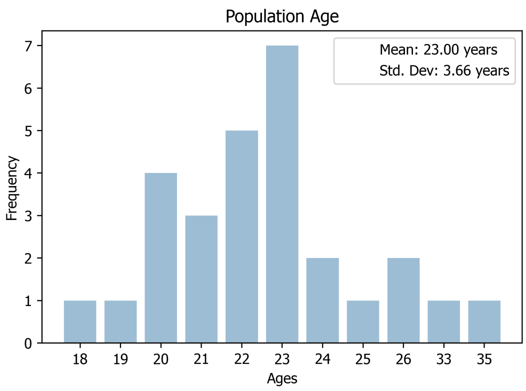
Dominant Hand	Participants(#)
Right-handed	28
Left-handed	0

(c) Participants Education Level

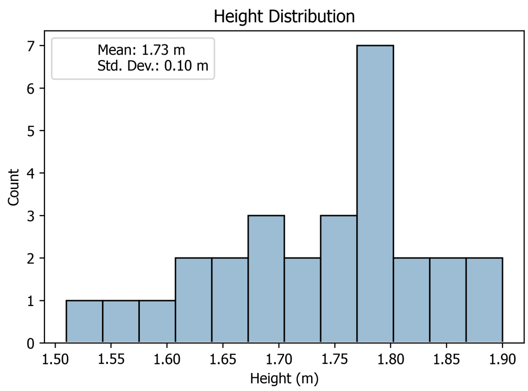
Education Level	Participants(#)
High School	5
Bachelor's	20
Master's	3

(d) Participants Visual Impairment.

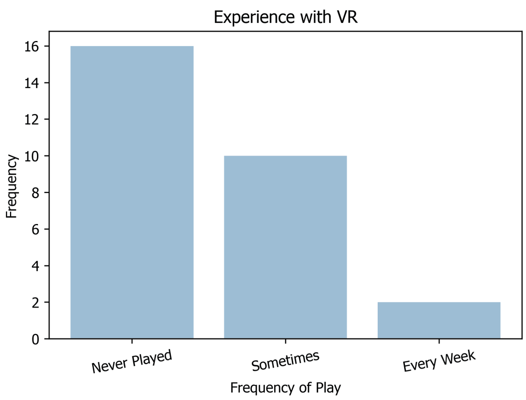
Visual Impairment	Participants(#)
Yes	10
No	18



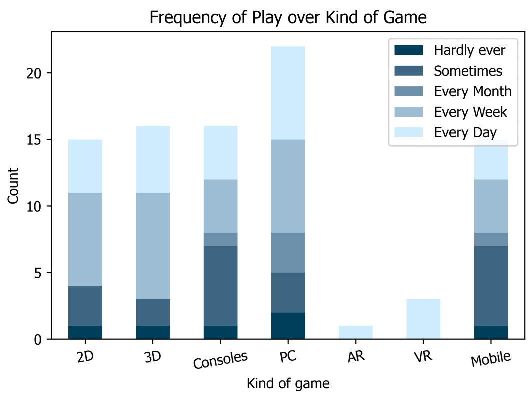
(a) Population age.



(b) Population height.



(c) Experience with VR.



(d) Frequency of play.

Figure 5.2: Population demographic graphs.

of play over kind of game. In general, 9 participants never or rarely play video games, and 19 participants play daily, weekly or monthly.

5.2.2 Spatial Function Scenario

In order to examine if there was a difference in completion time and subjective ease between the four conditions (F0, F1, F2, F3), statistical tests were conducted to compare the four tasks.

To choose an appropriate statistical test suitable to the data sets of completion time and subjective ease, we ran the Shapiro-Wilk test separately for each data set. The results determined that data was not normally distributed. That said, the statistical test used to compare the four conditions was the Friedman test[1], a non-parametric test equivalent of a one-way ANOVA with repeated measures, used when participants have been subjected to two or more conditions that are intended to be compared. Friedman test can be applied to ordinal or continuous values.

If the null hypothesis of the Friedman test was rejected, that implies that there was at least one pair of spatial functions whose distributions were different at a 5% significance level ($\alpha = 0.05$). To identify which pairs were different, we performed post hoc analysis with Wilcoxon signed-rank with Bonferroni correction to determine significantly different pairs. Table 5.3 presents the outcome of the statistical tests.

Completion Time

Friedman test revealed a statistically significant difference in completion time when comparing the four spatial functions ($\chi^2(3) = 64.757$, $p < 0.001$). Post hoc analysis with Wilcoxon signed-rank tests with a Bonferroni correction ($p = 0.0125$) resulted in significant differences between the pairs grey shaded in Table 5.3a. All possible permutations among the four conditions were compared, and all showed significant differences except for the comparison between the linear function F1 and the hyperbolic function F3 ($Z = -1.913$, $p = 0.056$).

Thus, we can see that the completion time varied significantly depending on the mathematical function used to map the objects on the virtual table. Participants showed better performance in the task whose playing area is similar to the real world, without spatial distortion (F0). Among the morphing functions, the one that performed best was the linear function (F1); the one with the lowest performance was the hyperbolic tangent function (F2).

Subjective Ease

From the results shown in Table 5.3b, the participants considered F0 the easiest task. Comparing the three space-morphing functions, the task named as most difficult was

[1] Friedman Test in SPSS Statistics: https://statistics.laerd.com/spss-tutorials/friedman-test-using-spss-statistics.php - Last accessed 22/11/2021

Table 5.3: Statistical results regarding completion time (Table 5.3a) and subjective ease (Table 5.3b) in the Spatial Function Scenario. The grey shaded cells highlight statistically significant differences between conditions.

(a) Statistics regarding task completion time.

	Completion Time (seconds)		**Friedman Test** α = 0.05		**Pairwise Comparisons**		
Conditions	*Mean*	*Std. Dev.*	χ^2	*p*	*Pair*	*Z*	*p*
F0 - Baseline	110.41	42.48	64.76	**5.65×10^{-14}**	F0 - F1	-4.60	**$4{,}00 \times 10^{-6}$**
F1 - Linear	252.29	100.85			F0 - F2	-4.62	**$4{,}00 \times 10^{-6}$**
F2 - Hyp.Tan.	397.22	171.93			F0 - F3	-4.62	**$4{,}00 \times 10^{-6}$**
F3 - Inv. Hyp. Tan.	286.95	84.53			F1 - F2	-4.49	**$7{,}00 \times 10^{-6}$**
					F1 - F3	-1.91	5.58×10^{-2}
					F2 - F3	-3.48	**4.94×10^{-4}**

(b) Statistics regarding task subjective ease.

	Subjective Ease (7-point Likert scale)			**Friedman Test** α = 0.05		**Pairwise Comparisons**		
Conditions	*Median*	*Q1*	*Q3*	χ^2	*p*	*Pair*	*Z*	*p*
F0 - Baseline	7.00	6.00	7.00	57.07	**2.48×10^{-12}**	F0 - F1	-4.18	**2.90×10^{-5}**
F1 - Linear	5.00	4.00	6.00			F0 - F2	-4.56	**5.00×10^{-6}**
F2 - Hyp.Tan.	4.00	3.00	5.00			F0 - F3	-4.43	**1.00×10^{-5}**
F3 - Inv. Hyp. Tan.	5.00	4.00	6.00			F1 - F2	-3.95	**7.90×10^{-5}**
						F1 - F3	-1.27	2.04×10^{-1}
						F2 - F3	-3.43	**5.94×10^{-4}**

F2. Tasks F1 and F3 were similar from the user's perspective since they did not show significantly different levels of subjective ease (Z = -1.271, p = 0.204).

Therefore, the condition without morphing (F0), in which the virtual area recreates the familiar behaviour of the real world, was considered by the participants the easiest among the four. Among the three morphing functions, the easiest one was the linear function (F1), which increases the space while preserving the properties of F0; the most challenging one was the hyperbolic function F2, which requires the user to make more precise movements to place the objects on targets in the center of the table. Additionally, participants found the tasks led by F1 and F3 to be similar in ease, even though they comprised very different geometries.

Observations

When the virtual playing area was augmented to cover the entire virtual table, four participants' first reaction was to get up from their chair to reach the (virtual) objects that were farther away; after a few seconds, they realized that, although the virtual area was enlarged, the physical objects were still in front of them. From the comments made during the experiment, participants mentioned that under conditions F1 and F3, the task seemed challenging at first glance, but they eventually adapted quickly and felt that they had more space to move the objects. In contrast, under condition F2, participants felt that the (physical) objects were always colliding, even though they saw the objects far apart on the (virtual) table. The most recurrent comment in F2 was about the difficulty in dragging objects to the center of the virtual table: "It seems that the objects move faster on the edges, which makes it difficult to place them on targets in the center of the table.". In condition F3, nine participants reported having more difficulty placing the objects on targets at the corners of the table; although some of the remaining participants found the task easier than F1 or F2, they said they did not detect much difference in the objects' behaviour.

Discussion

All morphing functions (F1, F2 and F3) showed significant differences in completion times and subjective ease compared with the baseline (F0). These results were expected since the baseline task occurred in a familiar Euclidean space where the user moves objects as in everyday experiences.

Of the three morphing functions, F1 acquired the best performance results and showed to be the easiest for participants. It was clear that task F2 was the most challenging since it showed longer completion time and lower subjective ease. The hyperbolic tangent properties in condition F2 justify the struggle reported by participants in moving objects to the table center. A minimal displacement at the ends of the table gets the object to go from one end of the table to the other (on the same axis) quickly. However, to drag the virtual object to the middle requires a much larger physical movement. This behaviour showed to be the least intuitive for the participants.

There was no significant difference in completion time or subjective ease between linear function F1 and hyperbolic function F3. In fact, most participants claimed to notice no difference between these two tasks. This weak dissimilarity can be justified because both functions exhibit identical behaviour over much of the playing area, distinguishing only at the table ends. Nevertheless, some participants noticed the particularities of the inverse hyperbolic tangent function used in F3, which gives objects the illusion of moving faster at the ends of the table. This property justifies the effort felt by some participants to place objects on targets farther from the center of the playing area since it required more precise movements.

All participants successfully completed all tasks, which showed the feasibility of the studied Euclidean and hyperbolic spaces. The completion time results are in line with the subjective ease results: F1 obtained the best performance and was also the easiest task for users; F2 got the lowest performance and showed the most challenging for users. From the users' comments, both morphing F1 and F3 conditions have succeeded in creating the illusion of a wider space to move tangible objects. Furthermore, the non-differentiation between F1 and F3 may suggest that applying non-Euclidean geometry in VR may be helpful in some tasks. In the present scenario, F3 makes it faster to reach the extremes of the table without losing performance compared with F1.

5.2.3 Object Size Scenario

In this scenario, we are interested in investigating whether incongruence between the size of physical and virtual objects influences user performance or preference. To this end, we compared the completion times for the three conditions (S0, S1, S2) and analysed the answers given by the participants to the *preference question*. With this question, we aim to examine particularly whether there is an obvious preference for the normal size (S0) of virtual objects, i.e., without visuo-haptic incongruence.

Completion Time

The Shapiro-Wilk test showed a significant departure from normality for the completion time dataset. Therefore, the Friedman test was used to compare these data. The results obtained are presented in Table 5.4. There was a statistically significant difference in completion time depending on which object scale was displayed, $\chi^2(2) = 19.786$, p = < 0.001.

Post hoc pairwise comparisons with Wilcoxon signed-rank test with a Bonferroni correction showed that participants took significantly longer to perform the task with the large virtual objects compared to the normal size (Z = -4.190, p < 0.001) and small size (Z = -3.848, p < 0.001). The task's completion time with the small object size did not show a significant difference compared to the baseline (Z = -0.524, p = 0.600).

Thus, on average, participants performed best when there was no visuo-haptic incongruence (S0) and worst when virtual objects were larger (S2). When the virtual objects were smaller (S1), the performance was not affected.

Table 5.4: Statistical results regarding participants' completion time for each size of the virtual objects. The shaded grey cells highlights statistically significant differences between conditions.

	Completion Time (seconds)		**Friedman Test** $\alpha = 0.05$		**Pairwise Comparisons**		
Conditions	*Mean*	Std. Dev.	χ^2	*p*	*Pair*	*Z*	*p*
S0 - Normal	109.18	28.46			S0 - S1	-0.52	6.00×10^{-1}
S1 - Small	113.26	25.93	19.79	$\mathbf{5.1 \times 10^{-5}}$	S0 - S2	-4.19	$\mathbf{2.80 \times 10^{-5}}$
S2 - Large	135.97	32.20			S1 - S2	-3.85	$\mathbf{1.19 \times 10^{-4}}$

Preference

After playing the Puzzle Game under the three virtual object size conditions, participants ranked them in order of preference, indicating which size they preferred to play with and which they preferred less.

From the stacked bar chart in Figure 5.3, we can see that the majority of the population (78.57%) preferred to perform the task with the normal size of the objects and preferred less when the virtual objects were larger (60.71%). As a second option, the condition indicated most frequently was referring to smaller objects (50.00%).

Thus, we can verify that there was a great tendency for participants to prefer firstly to perform the task when the virtual and haptic objects present the same size, i.e., under the conditions without visuo-haptic discordance (S0). Between the smallest and the largest size, participants show a preference for the smallest size (S1), tending to prefer last to perform the task with the larger objects (S2).

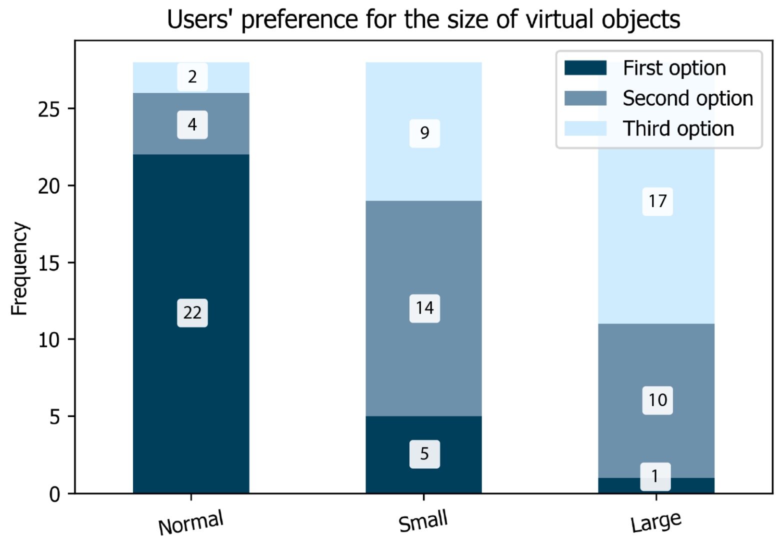


Figure 5.3: Stacked bar chart with the participants' answers collected on the *preference question*. The first option refers to the size preferred by the user; the third option is the least preferred object size.

Observations

In the two conditions in which the virtual objects were different sizes from the physical objects, there were two behaviours common to all participants: when the virtual objects were small (S1), participants brought the pieces closer together and shrunk their arms more; when the virtual objects were larger (S2) participants opened their arms, as if they were actually moving larger physical objects.

Participants who reported preferring S1 over S2 justified that with small objects, they felt there was more room at the table to move the objects with more detail; in opposition, when the objects were larger, they tended to grasp larger objects, and it seemed to take longer to reach the (physical) object. Participants who preferred S2 justified it by saying that the physical objects did not collide so much when using larger virtual objects.

Discussion

We can verify that the results obtained in the completion time are in line with the preference reported by the participants. The population showed better performance results when the physical and virtual objects were of the same size (S0). Accordingly, most participants chose S0 as the preferred condition. In turn, the condition with the larger virtual objects (S2) showed lower performance results and also proved to be the condition least elected by participants.

The results agree with the assumption that performance is better when there is concordance between visual and haptic information. However, all participants performed the other two tasks without any difficulty, proving their feasibility. Moreover, for smaller virtual objects, there was no significant impact on performance. These results suggest that extreme rigour may not be required to ensure the exact close size of tangible and virtual objects for performance to be preserved. In fact, the comments made by users throughout the session revealed advantages for both conditions: small objects create the illusion of a larger space, even if the play area (physical and virtual) remains exactly the same; large objects allow handling the physical objects without colliding with each other.

5.2.4 Hand Model Scenario

Firstly, this scenario explores whether the representation of the hands helps users perform tasks in the tangible VE. Complementarily, we aim to evaluate the two models under study - human model (H1) and abstract model (H2) - by comparing them in terms of performance and user preference.

Completion Time

After running the Shapiro-Wilk normality test, it was found that data reject the assumption of following a normal distribution. Therefore, the Friedman test was the statistic used to compare the completion times of the three conditions.

There was a statistically significant difference in completion time depending on which hand model was displayed, $\chi^2(2) = 6.000$, $p = 0.050$. Post hoc analysis with Wilcoxon signed-rank tests was conducted with a Bonferroni correction applied, resulting in a significance level set at $p < 0.017$. As highlighted in Table 5.5, the significant difference lies between H0 and H2 ($Z = -2.550$, $p = 0.011$), where condition H2 showed a longer completion time, suggesting that the abstract representation of hands led the user to take longer to complete the task.

We can thus verify that participants showed better performance when they executed the task without any spatial indication about the virtual hands (H0). Complementarily,

Table 5.5: Statistical results regarding participants' completion time for each hand model condition. The shaded grey cell highlights a statistically significant difference between conditions.

	Completion Time (seconds)		**Friedman Test** $\alpha = 0.05$		**Pairwise Comparisons**		
Conditions	*Mean*	Std. Dev.	χ^2	p	*Pair*	Z	p
H0 - No Hands	110.27	29.43			H0 - H1	-0.96	3.39×10^{-1}
H1 - Human Model	115.45	27.70	6.00	$\mathbf{4.99 \times 10^{-2}}$	H0 - H2	-2.55	$\mathbf{1.08 \times 10^{-2}}$
H2 - Abstract Model	122.04	26.50			H1 - H2	-1.43	1.51×10^{-1}

the results suggest that the abstract representation of hands (H2) led the user to take longer to complete the task. Relatively to the representation of the hand through a model similar to the human hand (H1), we can verify that it did not cause a significant impact on performance.

Preference

After playing the Puzzle Game under the three conditions, each participant was asked to rank the three conditions in order of preference, from most to least preferable. The collected answers are presented from the stacked bar chart in Figure 5.4.

Analysing the results, it is clear which hand model is most and least preferred by the participants. The majority of the population (71.43%) reported preferring to perform the task without any representation of the hands (H0). As a less preferable option, most

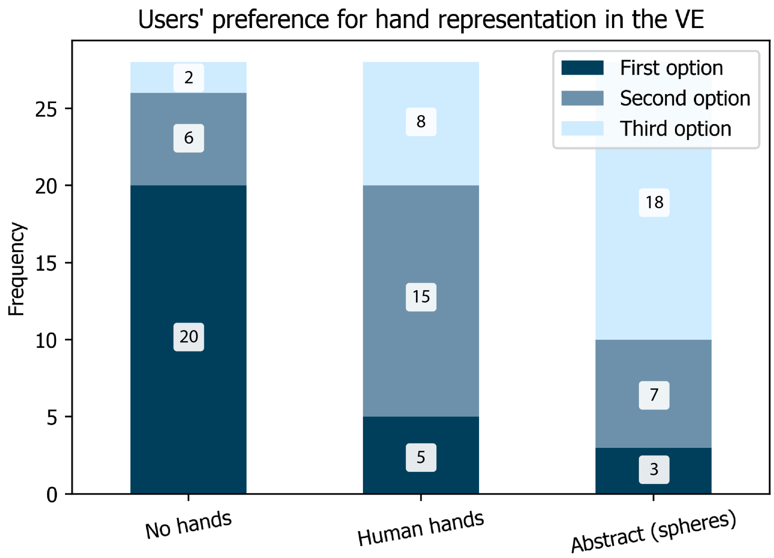


Figure 5.4: Stacked bar chart with the participants' answers collected on the *preference question*. The first option refers to the hand model preferred by the user; the third option is the least preferred model.

participants (64.29%) chose the abstract model (H2). In turn, the human model was more often (53.57%) chosen as the second option (H1).

Observations

The users who preferred performing the task without any hand representation gave identical justifications. As they could perceive the objects by touch, they did not feel the need to see the hands. In some cases, the hands even got in the way because they partially covered the (virtual) objects.

As mentioned in section 4.4.3, Vive's hand tracking presented occasional errors. Although sporadic, these tracking breaks proved to be distracting and annoying for users. However, some of the participants who chose the hand model as a second option complemented their choice by saying that if the tracking worked perfectly, they were likely to prefer this model in the first place.

When the abstract model appeared, some participants did not immediately realise that the spheres represented hands. In particular, nine participants thought that the spheres were obstacles to make the task more difficult since, in their opinion, the spheres covered their field of vision. Even so, three participants reported preferring the abstract model because it offered a visual reference about the position of the hands without being so distracting compared to the human model.

Discussion

Analysing the results obtained made it possible to verify that the representation of hands in the tangible VE does not contribute to improved performance. Although the human hand model (H1) did not significantly affect performance, it did not improve it either. Yet, users took more time to complete the abstract model (H2) task, showing a significant decrease in performance. The statistical results are in line with the comments made by the participants during the session: the hand models studied could have acted as obstacles to the performance of the proposed task.

Regarding the comparison of the human and abstract models in terms of participants' preference, we could verify that most participants preferred performing the task without any representation of the hands (H0). Comparing the human model (H1) and the abstract model (H2), the model more similar to the human hand was preferred by most participants.

The statistical results agree with the observations and comments made by the participants throughout the session. The population showed a great preference in performing the task without any hand representation, which turned out to be the condition with the best performance results. Similarly, the abstract model was the least comfortable for users, reflected in the weakest performance among the three conditions.

These findings suggest that hand representation may be dispensed in VEs with passive haptic feedback. Nevertheless, as ascertained by the related work surveyed in state of the art (section 2.2.2), this conclusion may be partly task-dependent. The objects used in our scenario had shapes and sizes easily perceived through touch, which made solving the puzzles intuitive without displaying information about the position of the hands in the virtual space.

5.2.5 Time Morphing Scenario

To investigate the influence of the seven visual delay conditions studied, we compared each of the conditions with the baseline condition D0. As justified in more detail in section subsection 5.2.2, the Friedman test was applied, followed by pairwise comparisons using Wilcoxon signed-rank tests with a Bonferroni correction. The statistical results obtained are presented in Table 5.6.

Table 5.6: Statistical results regarding completion time (Table 5.6a) and subjective ease (Table 5.6b) in the Time Morphing Scenario. The grey shaded cells highlight statistically significant differences between conditions.

(a) Statistics regarding task completion time.

	Completion Time (seconds)		**Friedman Test** *α = 0.05*		**Pairwise Comparisons**		
Conditions	*Mean*	*Std. Dev.*	χ^2	*p*	*Pair*	*Z*	*p*
D0 - 0 ms	106.69	23.09	142.46	**1.55×10^{-27}**	D0 - D20	-1.46	1.45×10^{-1}
D20 - 20 ms	102.94	21.00			D0 - D50	-0.68	4.95×10^{-1}
D50 - 50 ms	103.25	23.99			D0 - D100	-2.35	1.90×10^{-2}
D100 - 100 ms	118.47	29.88			D0 - D200	-3.48	**4.94×10^{-4}**
D200 - 200 ms	128.15	25.42			D0 - D500	-4.55	**$5{,}00 \times 10^{-6}$**
D500 - 500 ms	163.57	37.25			D0 - D1000	-4.62	**$4{,}00 \times 10^{-6}$**
D1000 - 1000 ms	199.24	61.52			D0 - DV	-4.62	**$4{,}00 \times 10^{-6}$**
DV - Variable	185.08	44.64			D1000 - DV	-1.23	2.19×10^{-1}

(b) Statistics regarding task subjective ease.

	Subjective ease (7-point Likert scale)			**Friedman Test** *α = 0.05*		**Pairwise Comparisons**		
Conditions	*Median*	*Q1*	*Q3*	χ^2	*p*	*Pair*	*Z*	*p*
D0 - 0 ms	7.00	7.00	7.00	83.12	**3.18×10^{-15}**	D0 - D20	-1.00	3.17×10^{-1}
D20 - 20 ms	7.00	7.00	7.00			D0 - D50	-0.58	5.64×10^{-1}
D50 - 50 ms	7.00	6.00	7.00			D0 - D100	-1.07	2.85×10^{-1}
D100 - 100 ms	7.00	6.00	7.00			D0 - D200	-1.48	1.38×10^{-1}
D200 - 200 ms	7.00	6.00	7.00			D0 - D500	-3.90	**9.70×10^{-5}**
D500 - 500 ms	6.00	5.25	7.00			D0 - D1000	-4.05	**5.10×10^{-5}**
D1000 - 1000 ms	5.00	4.00	6.00			D0 - DV	-3.96	**7.60×10^{-5}**
DV - Variable	5.00	4.00	7.00			D1000 - DV	-0.41	6.83×10^{-1}

Completion Time

As it is possible to verify by the values obtained in the pairwise comparisons (Table 5.6a), the task completion time was not significantly affected by delay values until 100 ms. The performance decreased significantly for delays from 200 ms ($Z = -3.484$, $p < 0.001$).

Subjective ease

For visual feedback delays up to 200 ms, subjective ease is also not significantly affected. Participants only noticed a significant change in task ease for delay values starting at 500 ms ($Z = -3.898$, $p < 0.001$). Additionally, the D1000 and DV conditions were compared to explore if the ease perceived by the user was different for constant versus non-constant delay. No difference was proven ($Z = -0.408$, $p > 0.683$).

To complement the data presented in Table 5.6b, Figure 5.5 provides a visual representation of the subjective ease evolution over the different levels of delay. Recalling that the participants were not previously informed that they would perform tasks under delay conditions, they only aimed to build the puzzles presented to them. Therefore, most participants only noticed that the virtual objects moved with delay when the latency was already very noticeable. Even so, through the justification given by the participants when rating the ease of each task, six participants stated that they did not notice any difference between the eight tasks, and five participants only detected delay under D1000 or DV conditions. To better analyse the low sensitivity these eleven participants had in detecting visual delay, we explored whether the participants' sensitivity to delay depends on their video game experience.

Figure 5.6 shows the minimum delay detected by each participant, grouped by how

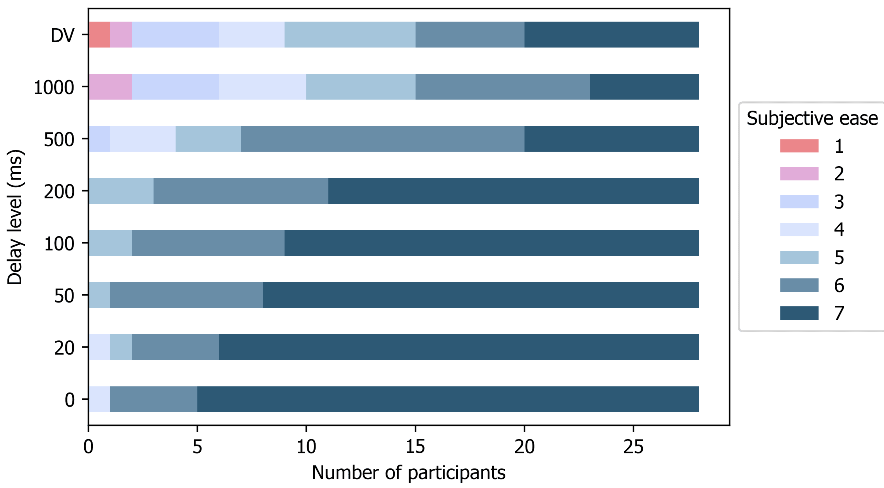


Figure 5.5: Bar chart with the subjective ease scores assigned at each delay level. The rating was given on a 7-point Likert scale (1=strongly disagree that the task was easy; 7=strongly agree that the task was easy).

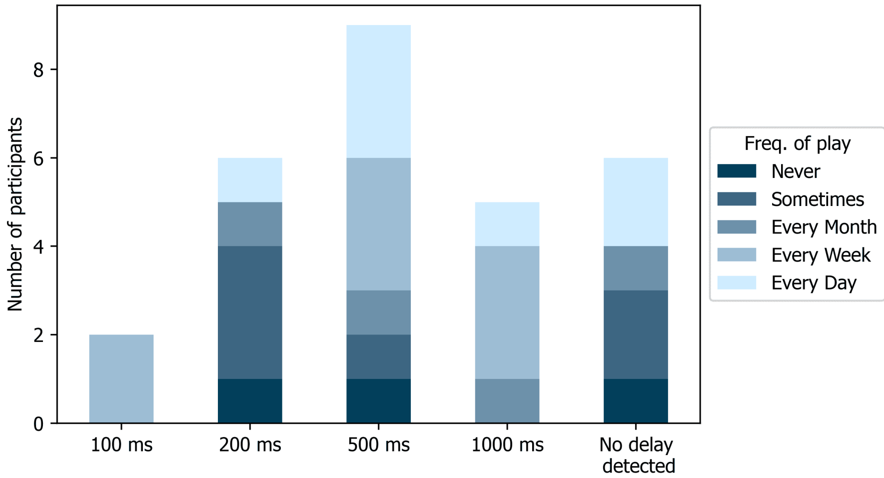


Figure 5.6: Minimum level of delay detected by each participant grouped by how often they play video games. No participant claimed to notice delay levels of less than 100 ms.

often he/she plays video games. No relationship was established to prove that participants who noticed smaller delays have more experience with video games or vice versa since each bar in the graph show different observed frequencies of play.

To sum up, although some participants detected latency for lower delay values, the perceived ease of constructing the puzzles was only significantly affected when the virtual objects moved and rotated with a delay of 500 ms.

Observations

With the increasing delay, most participants reported that the object rotation was the most challenging part in assembling the puzzle, especially in the final adjustments when the movements required more precision. When the virtual objects moved with delays of 500 ms and above, the users themselves said they were already using their sense of touch more than their vision. Another behaviour observed in all participants who did not detect delay was the (unconscious) move-and-wait strategy, discussed by Park et al. [70] (section 2.3.2). Participants continue performing the task only after receiving visual feedback on their actions, which led to them taking longer to complete the task.

Discussion

These results emphasized the humans' inability to detect slight discrepancies between visual and proprioceptive sensory information during interaction since 50% of the participants only reported high delay values (≥ 500 ms), and about 21.43% did not notice visual feedback delay at all. Figure 5.7 plots the increase in task completion time with the decrease in subjective ease. It is possible to observe a significant increase in the completion time from the 200 ms visual delay and a significant decrease in the ease perceived by users from 500 ms.

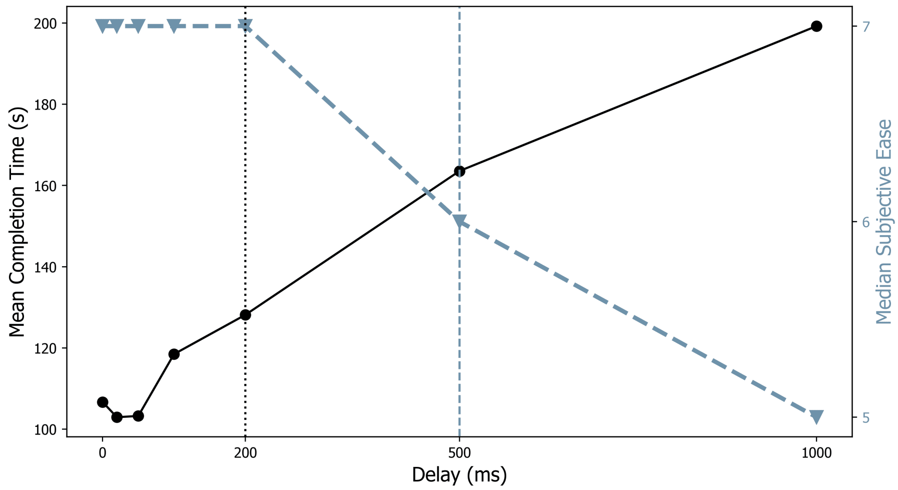


Figure 5.7: As delay increases, task completion time increases significantly from 200 ms delay, and at the same time subjective ease starts to decline.

These values are considerably higher compared with those reported by the related studies surveyed in the state-of-the-art (section 2.3.2). This discrepancy may be due to two factors: the task and the pre-experience briefing. Inevitably, the results obtained are always task-dependent, usually focusing on simple tasks. When the user is told that they will perform tasks under delay conditions, their goal becomes to find minimal delays. Although it is essential to determine the minimum delays detectable by humans, our goal was to determine from which delay the performance and ease of the task were affected, simulating a real context where users do not know in advance that there may be latency in the system.

These results may suggest the latency tolerable by participants and, consequently, the low-latency requirements may be relaxed in tangible VR applications. Additionally, our observations reveal the usefulness of including tangible objects in VEs. Otherwise, the user has to wait for visual feedback on their actions. We observed that haptic feedback helped users construct the puzzles since they reported using their sense of touch to put the pieces together. Although rotations and final adjustments always required some visual feedback, the tangible objects could be handled relying on haptic feedback.

5.2.6 Questionnaires

The post-session questionnaires and the *discomfort question* (displayed inside the VE) were mainly aimed at validating our VR Lab implementation to assess whether the VE proved engaging and without causing significant discomfort symptoms. The results of the questionnaires are presented below.

SSQ – Simulator Sickness Questionnaire

From the results acquired on the users' discomfort level at the three moments of the experiment (at the beginning, after all space morphing scenario and after the time morphing scenario), no variation in the users' discomfort level was found ($\chi^2(2) = 3.429$, p = 0.180). As it is possible to ascertain with Table 5.7, on a 7-point Likert scale, most participants reported rating 1 at the three moments of the experiment, corresponding to the minimum level of discomfort.

The post-experience SSQ questionnaires aimed to assess whether the complete experience caused discomfort effects. All reported symptoms were slight or moderate, and the most frequent symptoms were related to fatigue and eyestrain at the end of the session. Figure 5.8 presents the scores of the four SSQ groups.

Discussion The reported discomfort symptoms were primarily due to normal fatigue after 30-45 minutes in a virtual experience. It should also be noted that participants wore a mask during the entire session due to COVID-19 pandemic, which could have contributed to additional discomfort. Nevertheless, the low discomfort felt by the participants validates the design and implementation of the VR Lab setup, in terms of not

Table 5.7: Median and quartile values on the subjective question "I experience any symptoms of discomfort (e.g., fatigue, nausea)."Participants rated the statement on a 7-point Likert scale (1=strongly disagree; 7=strongly agree).

	Median	*Q1*	*Q3*
Before experience	1.00	-0.00	+0.75
After space morphing scenario	1.00	-0.00	+0.75
After time morphing scenario	1.00	-0.00	+1.00

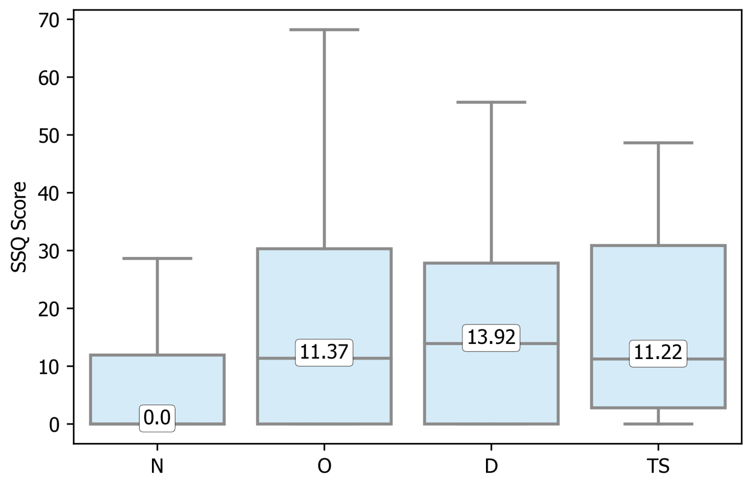


Figure 5.8: Boxplot with the Simulator Sickness Questionnaire (SSQ) scores after the complete experience. The different symptom groups along the x-axis are: Nausea (N), Oculomotor (O), Disorientation (D) and the Total Score (TS).

contributing to cybersickness symptoms.

IPQ – Igroup Presence Questionnaire

The sense of presence was addressed by the post-experience IPQ questionnaires, which are grouped into three subscales: *Spatial Presence* (questions 2-6), *Involvement* (questions 7-10) and *Experienced Realism* (questions 11-14). Each question was answered on a 5-point Likert scale.

Table 5.8 shows IPQ questions and the results obtained. *Spatial Presence* scores showed that the participants felt engaged and present in the VE. Although captivated by the virtual world, the scores in the *Involvement* questions suggest that users were aware of the real world during the experience. These results were expected since the user communicated with physical world entities throughout the experiment. *Experienced Realism* scores were also expected, as the environment was not intended to recreate real-world everyday experiences.

Discussion We can conclude that users feel involved and captivated by the VE. However, the awareness of the outside world can be justified. Participants were free to think aloud during the experiment, and many ended up establishing ongoing communication with the researcher to explain what they were thinking about the tasks. These conditions may account for the expected *Involvement* scores.

Table 5.8: IPQ scores.

IPQ Questions	*Med.*	*Q1*	*Q2*
1. I had a sense of "being there".	4.00	-0.75	+0.75
2. The VE surrounded me.	4.00	-0.00	+1.00
3. I was just perceiving pictures.	1.00	-0.00	+1.00
4. I did not feel present in the VE.	2.00	-1.00	+0.00
5. I had a sense of acting in the VE.	4.00	-1.00	+1.00
6. I felt present in the virtual space.	4.00	-0.00	+0.75
7. I was aware of the real world surrounding me.	4.00	-1.75	+0.75
8. I was not aware of my real environment.	2.00	-1.00	+1.00
9. I still paid attention to the real environment.	3.00	-1.00	+1.00
10. I was completely captivated by the VE.	4.00	-1.00	+0.00
11. How real did the VE seem to you?	3.00	-1.00	+1.00
12. The VE seem consistent with the real world?	2.50	-0.50	+0.50
13. How real did the VE seem to you?	2.00	-0.00	+1.00
14. The VE seemed more realistic than the real world.	1.00	-0.00	+1.00

5.3 Discussion

A population of 28 participants supports the results obtained. To reach more definitive conclusions, it would be necessary to extend the study to a larger population with more significant heterogeneity of professional and educational backgrounds, different ages, and different experiences in VR or video games. However, the acquired results allowed us to evidence some trends regarding the users' performance, opinion, and behaviour in the studied spatiotemporal conditions.

The statistical treatment from the data collected in each morphing scenario showed significant differences between some conditions and less significant differences between others. By cross-referencing the results of performance, subjective ease, preference and comments reported by the user during the experiment, it was possible to answer and substantiate the established research questions stipulated at the beginning of the study.

Q1 - Is there a significant difference in performance and subjective ease between performing tasks in a Euclidean space versus hyperbolic space?

Our results indicate that there might be a difference between performing tasks in a Euclidean space versus hyperbolic space. As expected, the baseline condition F0 showed to be the most comfortable for the users, as it simulated a Euclidean space, without morphing, identical to the real world. The three morphing functions (F1, F2, F3) differed significantly from baseline F0, both in performance and subjective ease. The linear space created by F1 tends to be the easiest for users, while the hyperbolic space of F2 was the most challenging. Although the results suggest a preference for Euclidean space, all participants accomplished and adapted without great difficulty to the tasks proposed in hyperbolic space. As a matter of fact, the non-differentiation between F1 and F3 may suggest that applying non-Euclidean geometry in VR can be a suitable approach to create the illusion of a larger space and help with some tasks. In the present scenario, F3 makes it faster to reach the extremes of the augmented table without losing performance compared with F1.

Q2 - After which delay value is there a significant difference in performance and subjective ease of the task?

The tasks performed in the tangible VE made it possible to observe a significant increase in completion time from 200 ms of visual delay. However, the ease perceived by the user only decreases significantly from 500 ms of delay, even if some participants noted lower delays. These results align with the premise that human beings can adapt to latency situations without great difficulty.

Q3 - In a tangible VR context, can the difference between the size of the physical object and its virtual representation affect task performance?

Our results indicate that the mismatch between physical and virtual objects can affect performance in haptic tasks. When virtual objects are larger than physical objects, the incongruence between visual and haptic information reveals a decrease in performance. However, when the virtual objects are smaller, the performance is not affected. This may suggest that performance can be preserved even if the physical and virtual objects do not have the exact dimensions.

Q4 - In a tangible VR context, does the hand representation help the user perform the proposed tasks?

Our study does not support the hypothesis that hand representation can significantly help users perform haptic tasks. In the developed VE, the tangible objects had shapes and sizes that showed appropriate for intuitive interaction, ruling out the need for a virtual hand model. Participants not only performed better in the no-hands condition (H0), but it was also their preferred condition. The hand models studied behaved as obstacles for some users by partially hiding the virtual objects. In particular, the abstract model (H2) caused a significant increase in task completion time.

Additionally, from the cybersickness (SSQ) and presence (IPQ) questionnaires, we validated our implementation of the VR Lab system. The results of the SSQ suggest that the environment created was pleasant for the users, who did not show symptoms of discomfort beyond the expected mild fatigue at the end of the experience. The IPQ results generally show participants' engagement with the virtual world, feeling present in the VR experience. However, the questions assessing user involvement with the VE showed that most participants continued to pay attention to the real world. This score can be justified by the design decision made regarding how questions were answered during the session (section 3.6), which was mainly aimed at encouraging the user to think aloud during the experience. This decision allowed gathering valuable information about the users' opinions. In return, it could have avoided the total abstraction of the real world. Although this score does not invalidate the implementation of the system, it can be a relevant result to motivate a different design of questionnaires in experiments where it is crucial to ensure the total immersion of users.

5.4 Summary

This chapter presented the procedure adopted to conduct the user study. The primary data collected during user testing were completion time, subjective ease, user preference and comments and behaviours uttered by users during the experience. Subsequently, appropriate statistical tests were used to process the results obtained in each morphing scenario.

Although the study was done with only 28 participants, it was possible to extract trends and significant differences between some conditions. The results of each morphing scenario were presented and discussed individually, accompanied with relevant conclusions that it was possible to draw.

The chapter ends with a more comprehensive discussion in which the research questions stipulated at the beginning of the study are answered.

6 Conclusion

The Virtual Reality (VR) capability to immerse the user in virtual worlds has been increasingly applied in the most diverse training scenarios, collaborative tasks, education, or entertainment. For the VR experience to fulfil its purpose, it is crucial to choose interaction techniques that fit the requirements of each task and that are appropriate to the user's needs.

Although VR can make the user feel present in a virtual simulation, studies on human perception have shown that humans perceive the real and the virtual world in different ways. Perception of space is usually underestimated, and time seems to pass faster when the Head-Mounted Display (HMD) is on. Understanding human perception in Virtual Environments (VEs) allows important insights to be extracted to create perceptually more accurate virtual worlds and more efficient systems.

Taking advantage of the user's inability to detect slight inconsistencies between visual and proprioceptive information makes it possible to design redirected techniques that create the illusion of a broader virtual space than the real-world play area. Redirected walking and redirected touching techniques are examples of methods that warp the space to guide the user's movements conveniently (e.g., avoiding colliding with obstacles). The human inability to detect slight rendering delays allows relaxing the low latency requirements and leverage system performance.

6.1 Conclusions

The work developed throughout this dissertation resulted in a functional prototype of the VR Lab - a virtual room with tangible interaction where user studies can be conducted to analyse different spatial and temporal morphing scenarios. The virtual space can be transformed in countless ways. Therefore, to guide the research, we stipulated four morphing scenarios, each addressing a research question. Although the results obtained are supported by a population of only 28 participants, we were able to extract interesting insights.

By comparing the adaptability to Euclidean and non-Euclidean - more specifically, hyperbolic - spaces, we can suggest that although participants were more comfortable performing the tasks under the familiar geometry of Euclidean spaces, they were able to adapt quickly to hyperbolic spaces. Moreover, there was no significant difference between the linear function F1 and the hyperbolic function F3. These results are in line with the work of Pisani et al. [12], and the research of Hart et al. [24, 25], which suggests that hyperbolic geometry can provide intuitive user navigation in virtual spaces (section 2.2.4). We believe that our work contributes as an incentive to further exploring hyperbolic spaces' applicability in VR. Enjoying the less restricted nature of non-Euclidean space may help create larger virtual areas or simplify navigation in more complex spaces without affecting user performance.

In a tangible VE, complementarily to vision, the user can also perceive the simulated world through touch. However, inconsistency between visual and haptic perception can affect performance. Notably, if the size of the virtual objects is larger than the size of the haptic objects, the visuo-haptic conflict can make the task of grasping objects misleading. Nevertheless, when the virtual object is smaller than the haptic object, our results show no significant difference in performance. Although participants tended to prefer performing the task with virtual and physical objects of the same size, they pointed out advantages for the other two sizes: when the virtual objects are smaller, the play area seems more spacious, making it easier to handle the objects; when the virtual objects are larger, the physical objects collide less. These findings provide insights for 3D visuo-haptic human-computer interaction design that can complement the experiments presented in section 2.2.1. In particular, the work of Siqueira et al. [59], which served as the main motivation to investigate further visuo-haptic conflict that can occur in tangible VEs.

The representation of hands in the VEs provides the user with information about the position of their hands in the virtual space. This information is usually indispensable in experiences without haptic feedback; users have to rely on vision to know where they are pointing or what objects they are grasping. Our study suggests that in a VE with passive haptic feedback, virtual hands are not indispensable. Moreover, in the scenario studied, the representation of hands was an obstacle for some participants who reported that the hand model blocked their view. These results join other related work presented in section 2.2.2. The experiments on hand model comparison conducted by Lin et al. [8], Grubert et al. [9] and Elbehery et al. [10] highlighted the importance of adopting appropriate hand models for each context. Depending on the task, minimalist models may be preferable over more realistic models, or vice versa. In the case explored, haptic information showed to be sufficient for users to handle tangible objects, thus ruling out the need to represent the hands within the virtual world.

Contributing to the systematic study on human tolerance to visual delay (section 2.3.2), our results suggest that, in a VE with visual and haptic stimuli, performance only started to be affected from 200 ms of visual delay. However, although some participants noticed the presence of lower delays (from 100 ms), the ease of the task was only shown to be affected from 500 ms visual delay onwards. Our results suggest that, in a tangible context, although users may not have immediate visual feedback, they can make up for this lack through haptic information and easily adapt to system delays. Establishing a tolerable system latency is essential to relax the low latency requirements in computationally demanding VR applications. The tolerable delay should take into account the task at hand. Our observations suggested that more detailed movements, such as minor rotational adjustments of objects, are more affected by visual delay than broader movements, such as moving the position of an object.

Additionally, our work contributes a VR application design capable of incorporating physical objects into the virtual experience using only a webcam. Our object tracking method can serve as a guideline for future works that aim to create tangible VEs without adding many more hardware devices to the standard VR setup.

6.2 Future Work

The VR Lab constituted a prototype that, although functional, can be improved and extended to more morphing conditions and scenarios beyond those studied in this dissertation.

Hand Tracking The hand tracking mechanism used was provided by the Vive Hand Tracking SDK, which used the built-in cameras of the HTC Vive Cosmos headset to track the hands. Although it offers satisfactory tracking, it shows weaknesses in accurately detecting the hand when the fingers are not clearly visible. For future work on hand representation in VR, other hand tracking approaches could be tried. An alternative is using devices such as Leap Motion or even taking advantage of the webcam already built into the VR Lab to use hand tracking based on computer vision algorithms.

Walking scenarios It would be interesting to extend the *Spatial Function Scenari*o and the *Time Morphing Scenario* to walking tasks. To study if hyperbolic functions applied to the user's position offers comfortable navigation and if the constant negative curvature of the hyperbolic geometry makes the dodging movements more intuitive. Walking tasks require more coordination between visual and motor information to avoid cybersickness. Applying the *Time Morphing Scenario* to the user's walk could contribute to establishing a tolerable latency in walking situations.

New conditions, tasks and tangible objects Although VR Lab is a prototype whose design was more focused on the four scenarios studied, it is possible to easily add different mathematical functions to manipulate space, explore different object sizes, evaluate different hand models and introduce different levels of delay. New tasks and games can also be designed to study existing or new scenarios. The method used to track the physical objects also allow adding tangible objects of different shapes and sizes to continue the study of haptic VEs.

Collaborative environment The system's architecture was designed to decouple the

VR application and the tangible objects tracking application. The communication between the two applications is done by a network layer using a client-server model. In the developed work, the VR application acts as the server, and the tracking application acts as the only client to send the data about the positions of the tangible objects. Future work could take advantage of this framework to create a multi-client environment to study the impact of spatiotemporal conditions in a collaborative context.

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A

Informed Consent Form

Para participar neste estudo deve estar ciente das condições da experiência, que dados serão recolhidos e como serão processados. Poderá apenas participar nesta sessão se, após ler esta informação, aceitar participar no estudo sob as condições em seguida enunciadas.

1. CONSIDERAÇÕES DE SAÚDE

Durante a sessão, usará um capacete de Realidade Virtual (VR) enquanto interage com alguns objetos físicos. Uma vez que todo o material será usado por múltiplos participantes, as devidas medidas de higienização serão tomadas. Nomeadamente, a troca da película facial do capacete, a desinfeção de todos os objetos envolvidos, da área de jogo e o arejamento do espaço. Para algumas pessoas, a utilização do capacete de VR pode provocar sintomas de desconforto como enjoo, tonturas, dor de cabeça, náuseas, entre outros. Caso sinta algum sintoma de desconforto, deverá sempre avisar-me para que possamos pausar ou terminar a sessão. Em qualquer outro momento da experiência, poderá sempre solicitar pausar ou terminar a sessão, caso considere necessário.

2. CONSIDERAÇÕES DE DADOS

Todos os dados recolhidos serão anonimizados antes de serem processados e apenas serão usados no contexto deste projeto académico. A informação recolhida será a presente no questionário que irá preencher no final da sessão, juntamente com valores recolhidos pelo sistema e observações visuais e verbais recolhidas por mim durante a sessão. Ao selecionar "Aceito", declara que aceita participar voluntariamente neste estudo académico, sob as condições de saúde enunciadas na secção 1, afirmando igualmente que tomou conhecimento e aceita que serão recolhidos e processados os dados supramencionados na secção 2.

Tomei conhecimento das condições enunciadas no Consentimento Informado e aceito participar no estudo em causa.

B

Characterization Questionnaire

The characterisation questionnaire was one of the post-session questionnaires presented to the participants in the user study. The questions that were asked in this questionnaire are listed below. Each question is accompanied by the type of answer required.

1. Age. **Short answer**: participant age.
2. Gender. **Single select multiple-choice**: Female; Male; Non-binary; I prefer not to answer; Other.
3. Height. **Short answer**: participant height.
4. Educational Level. **Single select multiple-choice**: Hight school; Bachelor degree; Master degree; Doctor of Philosophy degree; Other.
5. Dominant hand. **Single select multiple-choice**: Right; Left.
6. VR experience. **Single select multiple-choice**: I never used before; I already used it a few times; I use monthly; I use weekly; I use daily.
7. Video games experience. **Single select multiple-choice**: I never or rarely play; I play a few times; I play monthly; I play weekly; I play daily.
8. If you have experience with video games, which ones do you usually play? **Multiple-choice**: 2D games; 3D games; Console games; Computer games; AR games; VR games; Smartphones/Tablets games.
9. Do you have vision difficulties in everyday life, even when wearing glasses or contact lenses? **Single select multiple-choice**: Yes; No.
10. Additional comments on your participation in this experience. **Open answer**: participant comments.

I

Simulator Sickness Questionnaire

The SSQ consists of sixteen symptoms that must be rated with the scale from none, slight, moderate to severe. As explained by Kennedy et al. [71], the calculations include three representative subscores: Nausea-related (N), Oculomotor-related (O), Disorientation-related (D). Total Score (TS) is the score representing the overall severity of cybersickness.

1. General discomfort.
2. Fatigue
3. Headache
4. Eye strain
5. Difficulty focusing
6. Increased salivation
7. Sweating
8. Nausea
9. Difficulty concentrating
10. Fullness of head
11. Blurred vision
12. Dizzy (eyes open)
13. Dizzy (eyes closed)
14. Vertigo
15. Stomach awareness
16. Burping

II

Igroup Presence Questionnaire Questions

The IPQ [72] is composed of fourteen Likert-scale questions.

1. In the computer generated world I had a sense of "being there".
2. Somehow I felt that the virtual world surrounded me.
3. I felt like I was just perceiving pictures.
4. I did not feel present in the virtual space.
5. I had a sense of acting in the virtual space, rather than operating something from outside.
6. I felt present in the virtual space.
7. How aware were you of the real world surrounding while navigating in the virtual world? (i.e. sounds, room temperature, other people, etc.)?
8. I was not aware of my real environment.
9. I still paid attention to the real environment.
10. I was completely captivated by the virtual world.
11. How real did the virtual world seem to you (Compared to reality)?
12. How much did your experience in the virtual environment seem consistent with your real world experience?
13. How real did the virtual world seem to you (Compared to imagination)?
14. The virtual world seemed more realistic than the real world.