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User experience in virtual immersion: a study of scale factors for a similar perception in a CAVE and an HMD

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T H È S E

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Abstract

The title of this PhD is “User experience in virtual immersion: a study of scale factors for a similar perception in a CAVE and in an HMD”. Started in October 2019 under a cotutelle between two research laboratories, LISPEN (Laboratoire d’Ingénierie des Systèmes Physiques et Numériques) and IMI (Institut für Informationsmanagement im Ingenieurwesen), respectively belonging to ENSAM (Ecole Nationale Supérieure des Arts et Métiers) in France and KIT (Karlsruhe Institute of Technology) in Germany, this work was under the supervision of Pr. MERIENNE Frédéric, Dr. CHARDONNET Jean-Rémy and Pr. OVTCHAROVA Jivka. This thesis aims to compare two different devices, a CAVE Automatic Virtual Environment and Head-Mounted Displays. We started with the following statement: ’A CAVE automatic virtual environment and an immersive reality headset are two different technologies allowing immersion in a Virtual Environment. However, their differences may influence the user experience. To study this statement, we posed two research questions: Do a CAVE and a Head-Mounted Display offer different user experiences? And: ’Is it possible to have a similar user experience with these two different technologies?’. Our objectives were to explore the CAVE-HMD differences that might influence user behavior and experience. To answer these research questions, we built experiments to focus on fundamental differences between both devices, meaning the differences coming from the device’s characteristics. We carried out four experiments on four distinct features. The first experiment sought the differences in device weight. Indeed, worn weight might influence the distance perceived when walking; HMD’s weight range from 500 g to 1000 g, while CAVE’s worn weight is less than 100 g; thus, we have a ratio from x5 to x10 for the worn weight between HMDs and CAVEs. The second experiment focused on the difference between eyes-screen distances. With HMDs, screens are closer to the eyes (physically, optically, it is around two meters away), but for CAVEs, screens are physically farther. Additionally, users can move in CAVEs and thus get closer or farther from screens, changing where the virtual object is rendered compared to the screen (i.e., behind the screen, on the screen, or in front of). Moreover, our brain uses visual cues and eye reactions such as accommodation and vergence to estimate distances or size. Thus, the eyes-screen distance might influence perception. The third explored the difference between FOV (field of view) and FOR (Field of regard). For HMDs, we got a 360° FOR and 110° FOV, on average, against 270° (or less) CAVEs FOR and up to 220° FOV. The head rotation in CAVEs is restricted, making some specific tasks, such as exploring a narrow environment that asks users to look around and to rotate often their views more difficult, thereby influencing user experiences and behavior. The last one carried out focused on cybersickness. This factor is a well-documented field with HMDs devices, but not that much with CAVEs. To our knowledge, no studies have compared both systems on this specific topic. We developed an application to induce some cybersickness levels to compare both devices. Our findings show no significant difference in walk distance perceived for distances up to three meters. Therefore, the HMD's weight, which is negligible in the CAVE, can be ignored for an application that does not require physical displacement further than three meters. Short distances are harder to reproduce, no matter the devices, but both present accurate results for longer distances. Interestingly we did not find a significant difference in head rotation between devices, while, for the task designed, participants took more time to complete the whole application within the CAVE. We suppose that the time variation might originate from the time taken by participants to rotate in the CAVE. User feedbacks are firmly in favour of HMDs. The use of HMD is more natural, they can turn their heads, controls are more manageable, and the fact that boundaries are visible came as a disturbing point for the second display. From these results, we provide advice and guidelines on which device should be used according to the application's needs in terms of navigation, interaction, or user experience (time completion, feeling, motivation, cybersickness)

Keywords: Virtual Reality, CAVE, HMD, User experience, distance perception.

Résumé

Le sujet de ce doctorat est “L’expérience utilisateur en immersion virtuelle : une étude des facteurs d’échelle pour une perception similaire dans un CAVE et dans un HMD”. Démarré en octobre 2019 dans le cadre d’une cotutelle entre deux laboratoires de recherche, le LISPEN (Laboratoire d’Ingénierie des Systèmes Physiques et Numériques) et l’IMI (Institut für Informationsmanagement im Ingenieurwesen), appartenant respectivement à l’ENSAM (Ecole Nationale Supérieure des Arts et Métiers) en France et au KIT (Karlsruhe Institute of Technology) en Allemagne, ce travail a été réalisé sous la supervision du Pr. MERIENNE Frédéric, Dr. CHARDONNET Jean-Rémy et Pr. OVTCHAROVA Jivka. Cette thèse a pour but de comparer deux dispositifs différents, les CAVEs (CAVE Automatic Virtual Environment) et les casques de réalité immersive. Nous sommes partis de l’affirmation suivante : “Un CAVE et un casque de réalité immersive sont deux technologies différentes permettant toutes deux l’immersion dans un environnement virtuel”. Cependant, leurs différences pourraient influencer l’expérience de l’utilisateur. Pour étudier cette affirmation, nous avons posé deux questions de recherche : Un CAVE et un casque de réalité immersive offrent-ils des expériences utilisateur différentes ? Et : ’Est-il possible d’avoir une expérience utilisateur similaire avec ces deux technologies ?’. Nos objectifs étaient d’explorer les différences CAVE-HMD qui pourraient influencer le comportement et l’expérience de l’utilisateur. Pour répondre à ces questions de recherche, nous avons construit des expériences pour nous concentrer sur les différences fondamentales entre les deux dispositifs, c’est-à-dire les différences provenant des caractéristiques du dispositif. Nous avons réalisé quatre expériences sur quatre caractéristiques distinctes.

Le sujet de la première portait sur les différences de poids entre les dispositifs. En effet, le poids porté peut influencer la distance parcourue perçue lors de la marche ; le poids des HMD varie entre 500 et 1000 g, tandis que le poids des lunettes portées dans un CAVE est inférieur à 100 g ; nous avons donc un rapport de 5 à 10 fois pour le poids porté entre les HMD et les CAVE. La deuxième expérience portait sur la différence entre les distances œil-écran. Avec les HMD, les écrans sont plus proches des yeux (physiquement, optiquement, ils sont à environ deux mètres), mais pour un CAVE, les écrans sont physiquement plus éloignés. En outre, les utilisateurs peuvent se déplacer dans un CAVE et donc se rapprocher ou s'éloigner des écrans, ce qui modifie la façon dont est rendu l'objet virtuel par rapport à l'écran (c'est-à-dire derrière l'écran, sur l'écran ou devant). De plus, notre cerveau utilise des indices visuels et des réactions oculaires telles que l'accommodation et la vergence pour estimer les distances ou les tailles, ainsi cette distance yeux-écran peut influencer la perception. La troisième expérience a eu pour but d'explorer la différence entre champ de vision (FOV) et champ d'observation (FOR). Pour les HMD, nous avons un FOR de 360° et un FOV de 110°, en moyenne, contre 270° (ou moins) pour les CAVE et jusqu'à 220° de FOV. La rotation de la tête dans les CAVE en est donc limitée, ce qui rend plus difficile certaines tâches, comme l'exploration d'un environnement étroit qui demande aux utilisateurs de regarder autour d'eux et de tourner souvent leurs vues, ce qui peut influencer l'expérience et le comportement des utilisateurs. Le mal du simulateur a été le facteur étudié pour la dernière expérience, celui-ci est un domaine bien documenté avec les dispositifs HMD, mais pas autant avec les CAVE. A notre connaissance, aucune étude n'a comparé les deux systèmes sur ce sujet spécifique. Nous avons développé une application pour induire un certain niveau de cybersickness afin de comparer les deux dispositifs. Nos résultats ne montrent aucune différence significative dans la distance de marche perçue pour des distances allant jusqu'à trois mètres. Par conséquent, le poids du HMD, qui est négligeable dans le CAVE, peut être ignoré pour une application qui ne nécessite pas de déplacement physique au-delà de trois mètres, ce qui est valide dans la grande majorité des cas d'usage de ces dispositifs. Les courtes distances dans le cas d'un déplacement d'un objet sont plus difficiles à évaluer, quel que soit l'appareil, mais les deux présentent des résultats précis pour les distances plus longues. Il est intéressant de noter que nous n'avons pas trouvé de différence significative dans la rotation de la tête entre les appareils, alors que, pour la tâche conçue, les participants ont mis plus de temps à terminer l'application complète dans le CAVE. Nous supposons que cette variation de temps pourrait provenir du temps pris par les participants pour effectuer la rotation dans le CAVE. Les commentaires des utilisateurs sont unanimement en faveur des casques. L'utilisation du HMD est plus naturelle, ils peuvent tourner la tête, les contrôles sont plus maniables, et le fait que les limites physiques soient visibles a été un point perturbant pour le deuxième affichage pour certains participants. A partir de ces résultats, nous fournissons des conseils et une ligne directrice sur le dispositif à utiliser en fonction des besoins de l'application en termes de navigation, d'interaction ou d'expérience utilisateur (temps de réalisation, sentiment, motivation, cybersickness).

Mots-clés : Réalité virtuelle, CAVE, HMD, expérience utilisateur, perception à distance

Contents

Acknowledgements **3**

Abstract **5**

Résumé **7**

Introduction **19**

1 Research background **25**

1.1 Virtual reality 25

1.1.1 Definitions 25

1.1.2 History 27

1.1.3 Current research topics in VR 35

1.1.4 Hardwares (HMD/CAVE/Smartphone) 38

1.2 Interaction in Virtual Reality 42

1.2.1 Introduction 42

1.2.2 Interaction with objects 42

1.2.3 Movement within the virtual environment 43

1.2.4 Other ways to interact with virtual environments 45

1.3 Perception in virtual reality 46

1.3.1 Differences between virtual and real environments 47

1.3.2 Cybersickness . . . 49
1.3.3 User experience . . . 56
1.4 Conclusion . . . 58

2 User Experience and CAVE vs HMD 59

2.1 The MAUVE method . . . 59
2.1.1 VE system interface . . . 61
2.1.2 VE user interface . . . 64
2.2 CAVE versus HMD . . . 67
2.2.1 Visualization . . . 67
2.2.2 Interaction and Navigation . . . 69
2.2.3 Presence and Immersion . . . 71
2.2.4 Usefulness . . . 72
2.3 Scientific issues . . . 74
2.3.1 Cybersickness . . . 74
2.3.2 User behavior . . . 75
2.3.3 Synthesis . . . 76
2.3.4 Research questions . . . 78
2.3.5 Key factors . . . 79

3 Experimental Approach and Experiments 81

3.1 Device Characteristics . . . 81
3.1.1 BlueLemon . . . 81
3.1.2 Immersive CAVE room at the CRVM in Marseille . . . 82
3.1.3 Head-mounted display . . . 82
3.2 Impact of device weight on distance travel estimation . . . 84
3.2.1 Introduction . . . 84

3.2.2 Research questions and hypotheses 85
3.2.3 Experiment design 86
3.2.4 Results: Impact of weight on distance travel estimation 87
3.2.5 Discussion 88
3.3 Device impact in a navigation application 89
3.3.1 Introduction 89
3.3.2 Research questions and hypotheses 90
3.3.3 Experiment design 91
3.3.4 Results: Device impact in a navigation application 92
3.3.5 Discussion and Limitation 97
3.4 Impact of eye-screens distance for interaction distance estimation 98
3.4.1 Introduction 98
3.4.2 Research questions and hypotheses 98
3.4.3 Experiment design 99
3.4.4 Results: Interaction distance estimation 100
3.4.5 Discussion and Limitation 101
3.5 Which device to use to limit cybersickness 103
3.5.1 Introduction 103
3.5.2 Research questions and hypotheses 103
3.5.3 Experiment design 104
3.5.4 Results: Which device to limit cybersickness 105
3.5.5 Conclusion 107
3.5.6 Discussion and Limitation 107
3.6 Conclusion 108

Conclusion **111**

Bibliography **115**

Annexe **135**

4 Annexes **137**

4.1 Questionnaire for navigation experiment 137

4.2 Questionnaire for cybersickness experiment 137

Acronyms **147**

Partie Française **149**

4.3 Resumé Français 10% : 149

List of Tables

1 List of the differences between CAVE and HMD 21

1.1 Virtual Reality helmets specifications 31

1.2 Navigation techniques comparison 46

2.1 Differences between HMDs and CAVE system 77

3.1 HTC vive Pro and Quest 2 specification 83

3.2 Distance asked, error means to target distance and standard deviations 87

3.3 Navigation experiment, Mann-Whitney on VRSQ items 94

3.4 Experiment 2 mean and standard error for the distance error in percentage for the modality×distance 101

3.5 Mann-Whitney test results for each item of the VRSQ 106

List of Figures

1 Lecture plan . . . 24

1.1 Chapter 1, structure . . . 26

1.2 Stereoscopic devices . . . 28

1.3 Link Trainer . . . 29

1.4 Historic display devices . . . 30

1.5 Four different HMD released before 1995 . . . 30

1.6 Consumer and enterprise virtual reality market revenue worldwide . . . 31

1.7 Edutainment applications . . . 33

1.8 An example of users interacting with 3D models for product review tasks . . . 34

1.9 Collaborative virtual environments . . . 37

1.10 Different CAVE systems . . . 40

1.11 Four different interaction controls . . . 44

1.12 Three different rendering positions with a CAVE display . . . 48

1.13 The barrel effect . . . 49

1.14 Misery scale question . . . 53

1.15 Participant's heart-rate and temperature during a VR experiment . . . 54

1.16 Electrodermal activity of the same participant during the same period of time . . . 55

1.17 Postural stability before and after VR exposure . . . 55

1.18 Light setting in virtual environments . . . 57

2.1 Multi-criteria Assessment of Usability in Virtual Environment 60
2.2 Different FOV modification to reduce cybersickness 67
2.3 Difference between FOV and FOR 70
2.4 Three differents avatar representation 72

3.1 BlueLemon 82
3.2 CRVM's CAVE 83
3.3 Devices used for experiments 84
3.4 Different controllers used for experiments 84
3.5 Room for experiment about weight 87
3.6 Distance error in experiment on device weight 88
3.7 Virtual environment and help provided for the navigation task 91
3.8 Standardized mean of the participants' heart rate 93
3.9 VRSQ results for navigation experiment 94
3.10 Application data for navigation experiment 96
3.11 Participant movement for the navigation experiment 97
3.12 Virtual environment developed for experiment on distance perception 100
3.13 Experiment 2, distance to the target (in percentage). The mean and standard error for each modality and target distance 102
3.14 The fairy and environment developed for the experiment on cybersickness 104
3.15 CAVE VE for cybersickness experiment 105
3.16 VRSQ for the cybersickness application 107

Introduction

Context

This Ph.D thesis is in the field of Virtual Reality (VR). It aims to improve users' experience in immersive systems. More particularly, this work investigates *how users' perception of virtual environments (VE) is affected by the different characteristics of immersive systems.*

This work was carried out under a cotutelle between two research laboratories, LISPEN ("Laboratoire d'Ingénierie des Systèmes Physiques et Numériques (EA 7515)") and IMI ("Institut für Informationsmanagement im Ingenieurwesen"), respectively belonging to ENSAM ("Ecole Nationale Supérieure d'Arts et Métiers") in France and KIT ("Karlsruhe Intstitute of Technologie") in Germany, under the "French-German Institute for Industry of the future". This work is under the supervision of Pr. MERIENNE Frédéric, Dr. CHARDONNET Jean-Rémy and Pr. OVTCHAROVA Jivka. It was partly supported by a grant from the French-German University (UFA-DFH), No. CDFA 03-19, and by French government funding managed by the National Research Agency (ANR) under the Investments for the Future Program (PIA), grant ANR-21-ESRE-0030 (CONTINUUM).

Motivation

Virtual reality has been booming for several years. The availability of numerous low-cost application development and visualization tools (e.g., immersive headsets such as the Oculus Quest or HTC Vive) has allowed virtual reality to be democratized in many areas, such as product design, project review, health, construction, and training. Moreover, the benefits of including this technology are clear: a study published in 2018 by Capgemini shows that among 700 companies, 75% of them had increased their operational benefits by more than 10% by using virtual reality in their processes[1].

Although the first developments in virtual reality date back to the 1960s, several scientific barriers remain to achieve a massive diffusion of these technologies. Indeed, more information is necessary to fully understand users' behaviour and how they experience VR. Moreover, the variety of visualization devices, such as 3D displays, immersive headsets and immersive rooms (CAVEs), makes the treatment of these barriers more complex. Indeed, users' behaviour and experience in a VE might be affected by, among others, the type of the display, the exposure time, the application content and goal, the users' profile, their previous experience and their expectation of this type of technology. Moreover, cybersickness, which is a phenomenon inducing unwanted effects such as eyestrain, visual fatigue, headaches or nausea, and that appears mainly during virtual navigation tasks, is one of the main limits that prevents users from using VR comfortably. Numerous works have sought to understand and characterize this phenomenon in order to reduce its effects [Chardonnet et al., 2017, Aykent et al., 2014]. How the users interact in VR is another important key to understand how they perceive virtual environments. For instance, during a navigation task, some technologies do not allow unrestricted free movement in VEs or require the use of navigation techniques that are often unnatural and difficult to apprehend. Finally, some authors have shown that users' perception in virtual environments might differ depending on the devices used [Aykent et al., 2014, Dorado et al., 2017, Marsh et al., 2014, Tcha-Tokey et al., 2017].

In order to tackle these issues, the main objective of this work is to study the main factors that can influence the user experience for two different visualization devices, CAVE and immersive headsets.

Research problematic

Regarding previous observations, the following statement has been made: **"A CAVE automatic virtual environment and an immersive reality headset are two different technologies allowing immersion in a virtual environment but present both dissimilarities"**. This led to two main research questions:

- **Which are the device's characteristics that might affect users' experience while executing a particular task (e.g., navigation or manipulation)?**

[1] https://www.capgemini.com/news/press-releases/immersive-technology-has-arrived-ar-and-vr-set-to-become-mainstream-in-business-operations-in-the-next-3-years/

- **Is it possible to have a similar user experience with these two technologies?**

Different experiments focusing on the differences between both devices have been carried out to answer these questions.

Contribution

We first identified the differences between both immersive devices: head-mounted displays versus CAVE-like systems. Indeed, while HMD systems are commonly used for VR research in almost every domain (see section Figure 1.1.2), CAVE's systems are mainly used for collaborative research where the visualization of other users' bodies, face expressions and gestures are essential (see section subsection 1.1.3).

As presented hereafter, most of the differences between these devices concern physical characteristics (e.g., weight and lighting), while others relate to users' perception of themselves (e.g., self-body visualization) or the environment (e.g., optical flow) while using the device. A list of the differences is presented Table 1:

Price Ranges	**Screen edges**
Device worn-weight	**Eye-screen distances**
Intensity of the lighting	**Self-body visualization**
Display size and resolution	**Isolation from the real world**
Field of view (FOV) and field of regard (FOR)	**Optic flow (i.e., perceived movement)**

Table 1: List of the differences between CAVE and HMD

Furthermore, we analyzed how these devices' characteristics might impact user experience. In particular, we chose particular use cases, and we built experiments around these specific features. While past studies tend to focus on one of these devices alone, we set up experiments with both devices. Studies that compare CAVE-like systems and HMD exist [Steed and Parker, 2005, Ghinea et al., 2018, Naceri et al., 2009, Grechkin et al., 2010, Lin et al., 2019], however, in these works the comparison is not the main goal. Our work focuses on comparing CAVE and HMD systems for distance perception, when walking or when moving an object, for exploration and navigation tasks in vast environments, and for cybersickness.

With the results of these experiments, we can take a forward step into the comprehension of users' perception and experience in VR, according to the visualization device used, by providing usage advices.

Manuscript organization

This document is divided into three parts: literature review, on in-depth research on user experience in VR and studies using CAVE devices, thesis experiments and contributions (see Figure 1).

The first chapter presents a overview of VR tools' history, including applications and the most common research fields using these devices (see chapter 1). It is followed by a literature review on the different ways to interact with these systems, how the vision system works through them, and how cybersickness can be recorded. Furthermore, a review of the fundamental differences between the two devices and their potential to impact users' experience is presented. This literature review aims to cover user experience features and find which specific devices' characteristics might influence it (see chapter 2).

The third chapter starts by detailing the experimental approach followed. Based on that, different research directions have been explored. The four experiments we have conducted, one for each point extracted as a fundamental difference between the devices, are then presented. For each of them, the individual experimental design, results and discussion are presented (see chapter 3).

The first experiment sought the differences in devices' weight (see section 3.2). HMDs' weight ranges from 500g to 1000g, while CAVE glasses are less than 100g. Therefore, there is a ratio from x5 to x10 for the worn weight between HMDs and CAVEs. Indeed, the worn weight might influence the distance perceived when walking. In this case study, we analyzed walking distance estimation after a guided walk.

The second experiment explored the differences between the field of view (FOV) and field of regard (FOR) (see section 3.3). In fact, for HMDs, a 360° FOR and 110° FOV is, on average, provided by commercial devices, while a 270° (or less) FOR and up to 220° FOV is present in most CAVEs. Therefore, limiting the possibility of rotating the head in all possible directions in CAVEs' applications if the user wants to keep looking at the virtual environment. Indeed, it makes specific tasks, such as exploring a narrow environment, more difficult, influencing user experience and behaviour. To evoke this situation and analyze FOR and FOV impact, we designed an exploration task that asked the user to look around and often rotate their point of view.

The third experiment focused on the difference between eye-screen distances (see section 3.4). With HMDs, accommodation distance is fixed (on average around 0,75 to 1,5 meters) and determined by manufacturer, while for CAVEs, the accommodation distance might vary if the user move physically inside the system. Additionally, users can move physically in CAVEs and thus get closer or farther from screens, changing where the virtual object is rendered compared to the screen (i.e., behind the screen, on the screen, or in front of the screen). Moreover, the brain uses visual cues and eye reactions such as accommodation and vergence to estimate distances or sizes. Therefore, we hypothesized that this eye-screen distance might influence perception. To investigate this issue, we conducted an experiment demanding participants to estimate the egocentric distance to objects.

The last experiment focused on cybersickness (see section 3.5). Many researchers have focused on studying this factor with HMD devices, but little attention has been paid to CAVEs. To our knowledge, no studies have compared both systems on this specific topic. We developed an application to induce cybersickness symptoms to compare the effects produced by each device. The application chosen consisted of exploring wide and narrow environments through guided navigation.

Finally, the conclusion recapitulates the contributions of this thesis work, providing advices on which device should be used according to the application's needs and user experience, and speculates on the future directions of our research work in this area.

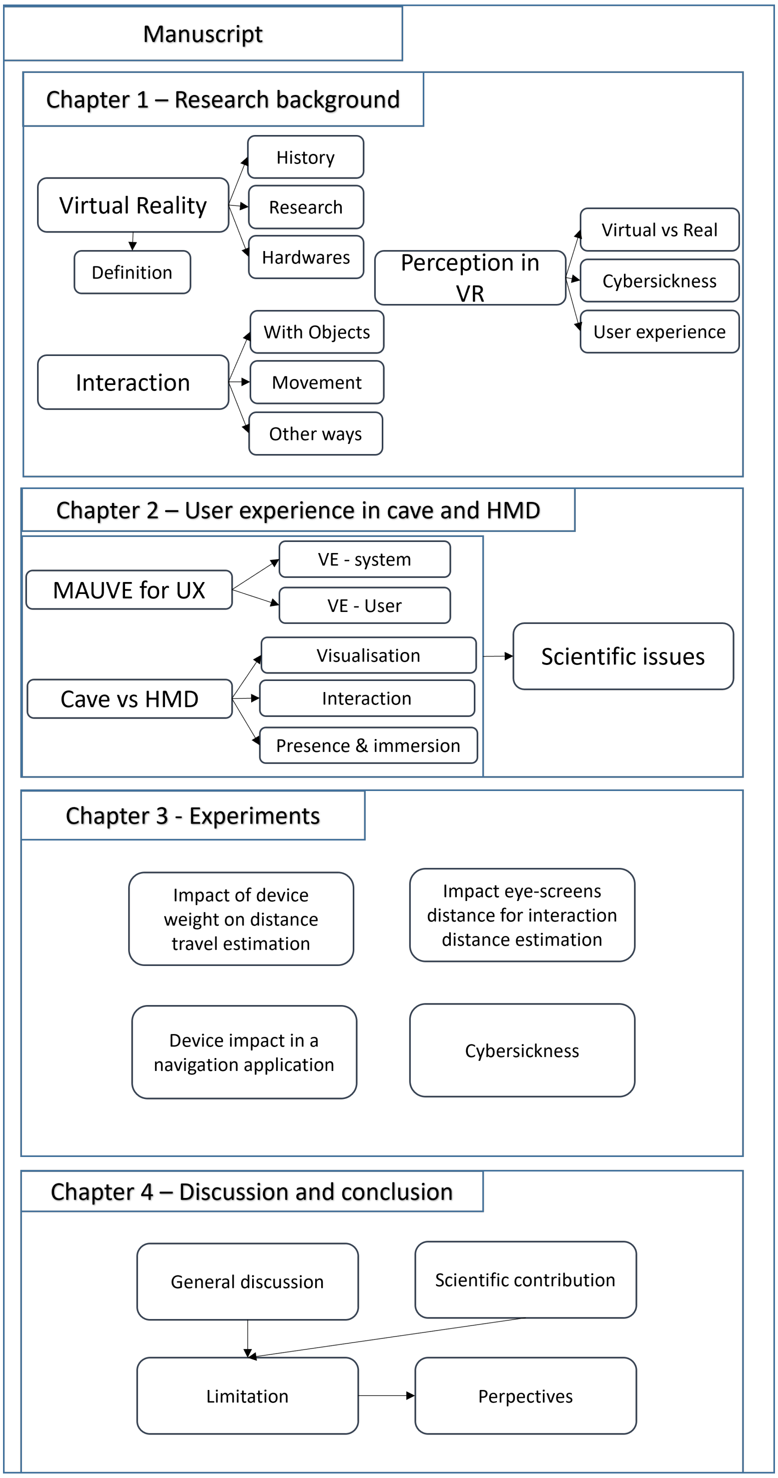


Figure 1: Lecture plan

Chapter 1

Research background

1.1 Virtual reality

This chapter starts with a short definition section. Then it focuses on presenting the history of virtual reality tools, the current usage of these technologies, and the main research topics. Moreover, the different ways to interact within virtual environments are presented and explained, with a focus on the pros and cons of each metaphor and technique. Finally, cybersickness, as a major issue related to VR usage, is presented with the objective of understanding how it affects users and how to rate its impact. This chapter is meant to present knowledge bases as keys to understanding chapter 2. The plan is depicted in Figure 1.1.

1.1.1 Definitions

Terms of virtual reality, mixed reality and augmented reality have been known for a while. Past researchers have tried to give accurate definitions, but depending on the sector and application that uses the technology, some variations exist [Muhanna, 2015]. Moreover, these definitions have evolved as technology changes. As a starting point, we provide the definition of the different terms employed in this manuscript and which relate to our subject of study: user experience in virtual reality for different display technologies.

Virtual reality (VR). Virtual reality is an artificial environment created by software and presented to the user in such a way that it is accepted as a real environment in which the user can interact. It primarily involves two of our five senses: sight and hearing. The simplest form of virtual reality is a 3D image that can be explored interactively on a personal computer, usually by using a keyboard or

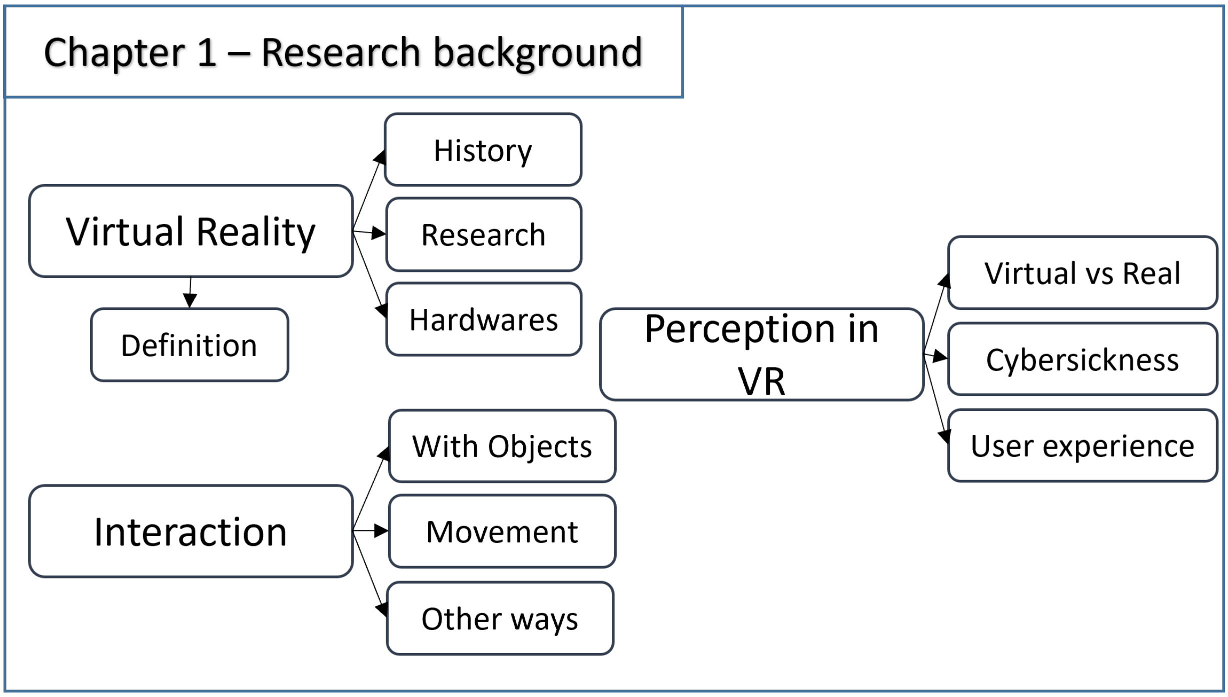


Figure 1.1: Chapter 1, structure

a mouse to move the content of the image or environment in a certain direction. More sophisticated technologies can be implemented, such as immersive rooms where sensors and haptic devices intersect to provide a tactile experience of the projected images[1].

Virtual Environment (VE). A virtual environment is any computer-generated environment where users can interact or move around. It can be a copy of reality but also a simulation of some aspects of it, a symbolic representation of a concept or phenomenon, or an entirely imaginary world [Fuchs et al., 2006].

Presence & Immersion Presence may be defined as a psychological sense of being in the virtual environment, as described by [Slater et al., 1994]. Reaching this specific user state is essential, specifically in VR applications, where it is important that the user feels like "being in the virtual world". The application needs certain features to reach the feeling of presence level. Immersion may be an extreme state, which is not reached in most serious applications. It usually appears when the user is really into the interaction or task, it may happen with entertainment applications, but it is more difficult to achieve through learning applications. It is often described as a state where the users are

[1] https://www.techtarget.com/whatis/definition/virtual-reality

not aware anymore of their surroundings [Stanney et al., 2003], where they might forget the time and even omit people who talk to them. It may be seen as the ultimate goal to reach through virtual reality applications.

Immersion can be defined as a state where the user is unaware of the real world around him; he does not notice time passed or even people talking to him. Findings indicate that immersion has the following features [Brown and Cairns, 2004, Jennett et al., 2008]:

- Lack of time awareness
- Loss of real-world awareness
- Involvement and a sense of being in the virtual environment

Immersion is linked to presence, but there is a slight difference between them. An application could induce one without the other; for instance, it may be challenging to generate presence with a puzzle game, but it can be easily immersive. Presence is also possible without immersion; some tedious/serious tasks in virtual reality, such as mopping or writing an essay, are less likely not to induce immersion. To induce immersion or presence, there are the virtual environment factors, which are all the visual features and environment behaviour (e.g., gravity, object reacting to collision), and the interaction factors, which are the user's interaction with the VE (e.g., moving, interacting with objects) [Brown and Cairns, 2004, Cheng and Cairns, 2005]. Still, if there is too much information, or if they are displayed in an unfunny manner, users will not want to reuse the application. It is therefore essential to find the right balance between fun and learning by adjusting visual cues, information, graphics, interactions or environmental behaviours.

1.1.2 History

This section gives a quick overview of the development of virtual reality technologies over the past years and how they are used today for industrial and research purposes.

Before 2000

Virtual reality systems appeared before the term "virtual reality" was defined. The first invention that is considered to be the first step in virtual reality display was invented in 1838 by Charles

Wheatstone and was called the “stereoscope”. This display device allows a user to perceive images in three dimensions through the use of stereoscopy.

Through the visualization of two side-by-side stereoscopic images, the user is able to see a 3D image with such a device. David Brewster later refined this technology in 1849 with the “Lenticular stereoscope”, and a commercial device based on William Gruber’s invention existed in 1939, called the “view-master” for photographs’ visualization. These three displays (see Figure 1.2) work similarly: to enable the sense of depth, two different viewpoints are displayed, one for each eye, with a slight shift of position between each viewpoint.

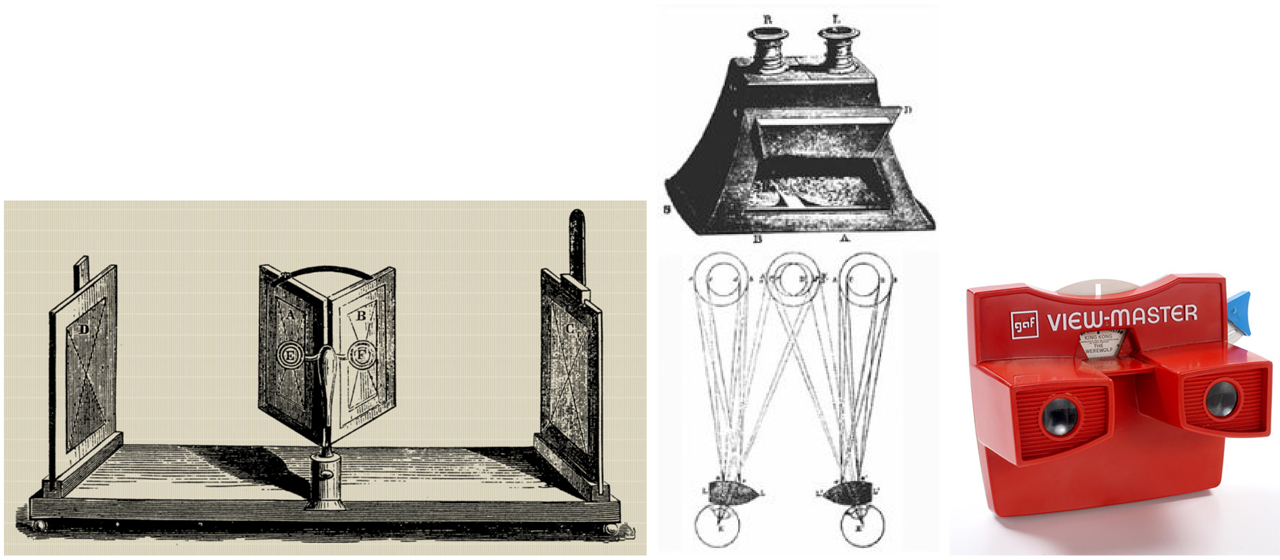


Figure 1.2: Stereoscopic devices. From left to right: “Stereoscope” (1838), “Lenticular stereoscope” designs from Brewster (1849), “View-master” device (1939)

In 1929, Edouard Link invented the “Link trainer”, a simulator (probably the first example of a commercial simulator) that gave users motion feedback. It was entirely electromechanical, controlled by motors to modify the pitch and roll, and a small motor-driven device mimicked turbulence and disturbances. It was designed to train airplane pilots and used during World War II as a training tool. This device did not provide any visual feedback. A picture of the first model made in 1929 is reproduced in Figure 1.3.

The “Sensorama”, imagined by Morton Heilig in 1955 and presented in 1962, involved immersive visualization with multisensory feedback, see Figure 1.4. Through this device, users could see stereoscopic 3D pictures thanks to the built-in stereoscopic displays. It was also provided with stereo

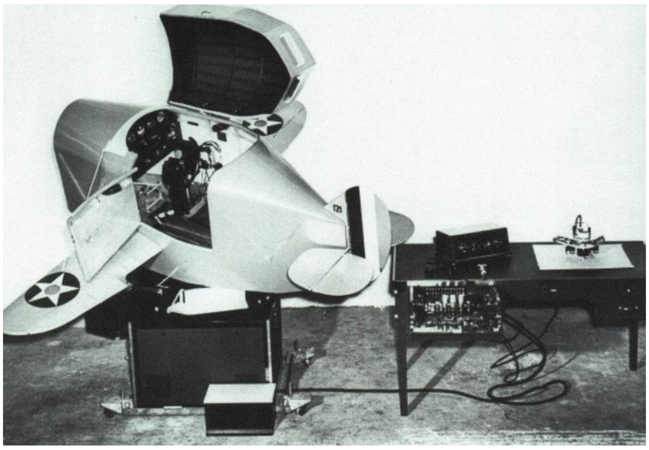


Figure 1.3: Link Trainer (1929)

speakers for listening, fans for simulating wind, a smell generator and a vibrating chair. It allowed visual and auditory immersion of a user in a previously filmed real scene.

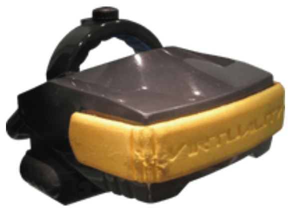
The next big step was the “Sword of Damocles”, created in 1968 by Ivan Sutherland during his PhD, see Figure 1.4. This device is recognized as the first head-mounted display (HMD), even though no body tracking of the users was possible, nor interaction with the virtual environment was provided. However, this display, comprising a semitransparent virtual reality helmet and a mechanical arm, is the first device to track the user’s head. Following that, Scott Fisher, who worked at NASA on the HMD development, improved the visualization of virtual environments, added a 3D sound system, and searched for different applications possible for such devices. Still, interaction with the VE was missing. Fisher worked then with Warren Robinett (an Atari game developer) and Jaron Lanier, who developed an interaction glove to create the first virtual interactable environment. In 1986, the first interactive virtual environment, as defined nowadays, was invented.

Recent times Virtual reality tools have experienced some commercial difficulties. The high price and low quality offered by early HMD have made these devices unusable for businesses and out of reach for households. Moreover, the low resolution and refresh rate caused users cybersickness. Since the end of the 80s, some companies have tried to spread these technologies, especially virtual reality headsets, through entertainment applications for private users or training applications and communication possibilities for professional users (e.g., exhibitions and employee training). Examples of these devices are the Atari Jaguar, the Virtual Boy from Nintendo, and the examples listed in

Figure 1.4: Historic display devices. Left: Sensorama - 1962. Right: Sword of Damocles - 1968

Figure 1.5 and Table 1.1[2]. Therefore, until the 21st century, HMDs were mainly used by and for research or big companies that could afford the investment.

(a) EyePhone



(b) Visette 1

(c) CyberMaxx

(d) VFX1

Figure 1.5: Four different HMD released before 1995

Over the past century, the computational capacity of computers has increased dramatically while the price and size of hardware have decreased. These three factors contributed to making VR devices more accessible and familiar in our society in the last decade. The video game industry made an early bet on wearable immersive devices and their entertainment possibilities. Indeed, several large companies have invested in developing HMDs, offering better accessibility and improving hardware

[2]https://vr-compare.com/compare

Table 1.1: Virtual Reality helmets specifications: EyePhone, Visette 1, CyberMaxx and VFX1

Manufacturer	VPL Research	Virtuality	VictorMaxx	Forte
Name	EyePhone	Visette 1	CyberMaxx	VFX1
Release date	June 1, 1989	October 7, 1991	November 1, 1994	January 1, 1994
Price	\$250000	\$60000	\$699	\$695
Resolution	320x240	276x372	505x230	263x230
Refresh rate	30 Hz	20 Hz	-	60 Hz

characteristics, see Figure 1.6[3,4]

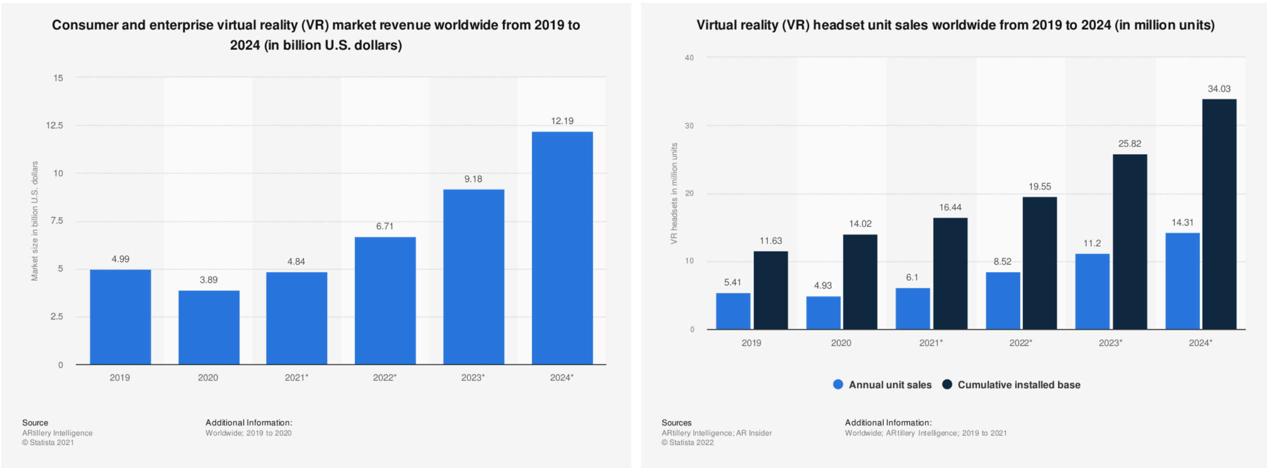


Figure 1.6: Left: Consumer and enterprise virtual reality market revenue worldwide from 2019 to 2024. Right: VR HMD units sold worldwide from 2019 to 2024

Today's usage of virtual environments

Edutainment Virtual reality, mixed reality or augmented reality can be used for edutainment purposes [Tcha-Tokey et al., 2017, King et al., 2018, Smith and Hamilton, 2015, Howard and Gutworth, 2020], allowing for innovative and different ways to teach and learn. These tools permit explaining more complex concepts by allowing students to practice or to see information from different points of view and experience learning through different feedback modalities [Cha et al., 2019, Smith and Hamilton, 2015]. Indeed, fields such as medical learning or engineering benefit greatly from the use of its tools in their learning processes [Dulina and Bartanusova, 2015, King et al., 2018, Zhang, 2017, Smith and Hamilton, 2015, Ghinea et al., 2018]. VR tools can be used to teach in a safer environment,

[3]https://www.statista.com/statistics/499714/global-virtual-reality-gaming-sales-revenue/
[4]https://www.statista.com/statistics/677096/vr-headsets-worldwide/ depicts the current expected evolution of the VR market.

especially for hazardous work such as nuclear industrial maintenance or excavation training. This is also true for third-party safety. For example, in the medical field, it is safer and easier to train with a virtual body than with real patients [Hagita et al., 2020, Buckley et al., 2012]. VR usage for learning also presents the advantages of accustoming students to particular rooms or working environments. Indeed, during virtual training, learners are immersed in an environment that could replicate the real work environment, which is not usually reproduced in most training rooms [King et al., 2018].

Moreover, some learners stated that using VR increased their confidence, and they would like to see VR edutainment used more often. A study carried out in 2020 on the use of VR tools in higher education institutions [Radianti et al., 2020] shows that VR tools are mainly used in engineering and computer science fields for procedural and practical knowledge. Unsurprisingly, these tools were not shown to be suitable for explicit theoretical understanding (e.g., text). The key results points about their investigation are that learners who used VR tools felt more engaged, spent more time on learning tasks, and acquired better cognitive, psychomotor, and affective skills than students who used conventional tools. On top of that, a new learning style is emerging, a more personalized way of acquiring knowledge, where students can access information from anywhere and on any device. Some universities are starting to use VR tools, and although the initial price may seem high, the ongoing cost is affordable, mostly lower if compared with older tools (e.g., tools for industrial processes or mannequins for medical studies). Moreover, it allows students from all over the world to receive specific training without the intervention of an in-situ lecturer [King et al., 2018]. Furthermore, VR tools for autonomous training can also provide an objective evaluation (e.g., completion time or accuracy for movement or task execution) [Satava, 2001]. This is not the case with physical simulators, which require an evaluator to ensure that the task is correctly performed and to provide real-time feedback to the trainees.

In addition to the fact that the previous case studies have proven to be effective in teaching good practices, users of these new technologies appreciate them and are willing to continue using these types of applications [Tcha-Tokey et al., 2017, Smith and Hamilton, 2015]. Indeed, gamification and learning by doing induce a better engagement among participants [King et al., 2018]. See Figure 1.7 for two examples of edutainment VR applications.

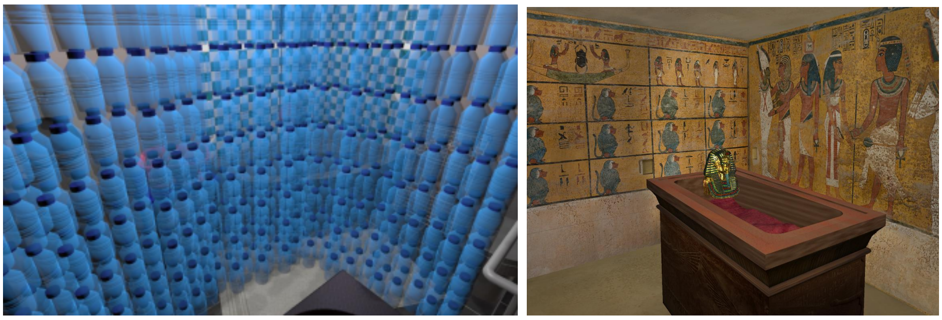


Figure 1.7: Edutainment applications. Left: Developed for a county house to help users reduce their energy expenses. Right: "KingTut VR" is an online application to learn about Tutankhamen

Manufacturing VR makes it easier to involve the end users in the design process. For example, a technician can test a tool before it goes into production, and a buyer can visit a property that is not yet built. Indeed, the end users can comment and give their opinion before it is too late, reducing the iteration times and getting results better aligned with expectations. The engineering and architecture industries are the first areas to adopt this technology. The first one, thanks to computer-aided design (CAD) models, can, for instance, benefit from VR visualization applications that favor easy interpretation, tests on ergonomics, and immersive discussion during a product review. Indeed, many advantages are presented by CAD models coupled with new technology: increase in productivity, reduction of errors during the design phase, the possibility to make simple real-time adjustments, and the ability to transfer a readable file that can be used by third-party software. Developers can make VR applications that easily include these models and intend to facilitate discussion and interpretation[5]. For the architecture field, VR applications can be made with the help of building information models (BIM) that allow the different actors from a project to exchange their subject-specific files (e.g., electrical wiring plans, security paths, etc.). BIM simplifies and accelerates the work of each team, including the development of VR applications to show the final product to users [Sidani et al., 2019]. By showing the final product to the end users, asking for their advice and involving them from the beginning of the product development, it is easier to adapt the product to their needs and detect those changes in the early stages of the process. Companies that use immersive technologies benefit financially, generally by reducing the cost of their production line and improving the quality of their products [Dulina and Bartanusova, 2015, Cha et al., 2019, King et al., 2018].

In terms of technology, 2D displays are still widely used. Indeed, these devices have the advantage

[5] https://drexel.edu/cci/stories/advantages-and-disadvantages-of-cad/

of being familiar to general users, easier to develop for the manufacturer and require a lower rendering capacity. However, they have two major flaws that can significantly influence the end users' decisions, especially in the building domain: the lack of immersion and the altered perception of distance. In order to tackle these issues, a study tried to provide an optimal workstation for employees [Dulina and Bartanusova, 2015]. To achieve this, they used a CAVE system. They asked employees to test a workstation through a CAVE, where they were able to change every aspect of it within the application without any production cost. In other words, they do not have to create the physical workstation and modify it according to the recommendation or feedback from employees, which can be expensive and time-consuming. Another study explored the usability for architecture design [Cha et al., 2019]. In this study, authors used virtual environments to compare different ceiling types and heights before construction began, concluding that VE could be used to choose the most appropriate architectural designs before construction, saving money and time. See Figure 1.8 for two examples of manufacturing VR applications.

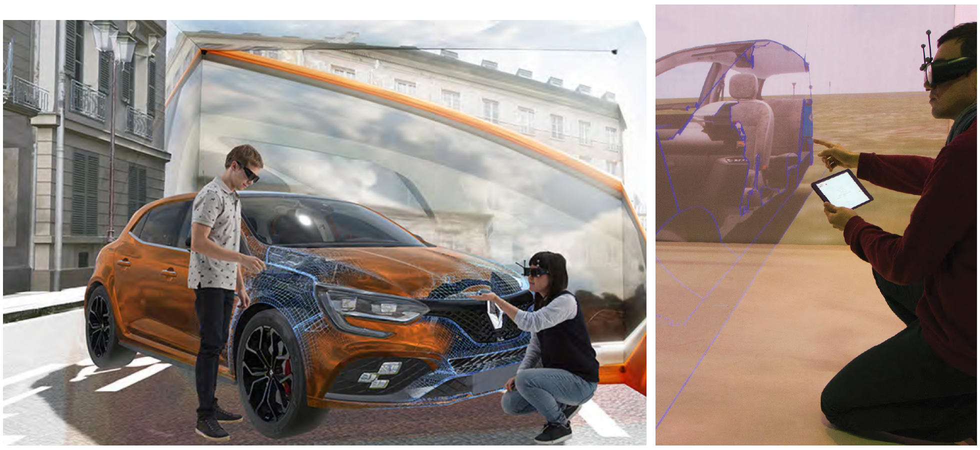


Figure 1.8: An example of users interacting with 3D models for product review tasks

The next steps **VR shopping applications** are promising because they offer high customer immersion and can bring new ways to buy stuff and groceries without the constraints of going to the stores or respecting opening hours. Some major shopping companies have already launched or at least developed a prototype of a VR shop. Experiments show that VR enhances consumer learning about products and allows a more straightforward analysis of their behaviour [Peukert et al., 2019]. Previous e-commerce research has shown that the ability to look at the product from all angles, to grasp it and see how it works, providing a near-reality experience, positively improves product judgment.

Virtual reality might become more present for the general public as recently announced by **Meta company** in 2021 (formerly Facebook) with the creation of the **Metaverse**. This digital universe will be a set of spaces, games and applications that everyone will be able to access easily. It is supposed to be fully visitable via VR and AR tools, where everyone would have an avatar representation to interact with the rest of the environment and users. Different kinds of activities will be available (e.g., sports, conferences, learning and gaming). Moreover, many possibilities for purchasing are expected, such as services or virtual goods, in particular, to personalize avatars or virtual possessions. Eventually, the "Metaverse" should offer an experience similar to what the movie Ready Player's One (2018) depicts.

1.1.3 Current research topics in VR

Human behavior Virtual environments allow the creation of specific real-life situations. This is particularly important in driving simulation, industrial research, human social skills and pedestrian behaviour analysis. As for training, VR reduces risks for participants and permits more data collection. For instance, tracking the exact users' path during locomotion and obtaining gaze data is possible through VR systems. VEs are commonly used in the driving simulation field [Lucas et al., 2020, Reinhard et al., 2017], while the use for pedestrian research is limited and more recent [Schneider and Bengler, 2020]. The principal scientific and technological challenges related to those research areas concern the realism of the simulated experience. Indeed, the virtual environment's fidelity and the whole simulation's fidelity (e.g., the realism of the feedback and the ecological validity of the situations and experiences presented) might cause researchers to question the validity of the collected data. For instance, a VR application that allows users to do long-distance walking easily reaches the limits of current VR devices, requiring a recalibration of the system to reposition the user, and needs to warrant that this is completely transparent for him/her.

VEs might also be used for virtual reality exposure therapy (VRET), as explored by Krijn et al. in 2004 [Krijn et al., 2004]. They compared "Vivo" (the golden standard for acrophobia therapy at that time) with their application. Participants in their study followed standardized acrophobia therapy treatment, and the number of sessions and time between exposition and exposure time was recorded. The results show that virtual reality environment therapy is as effective as the "Vivo" therapy and more than conventional therapies.

Embodiment Research on embodiment is also a recurrent topic of VR research. The representations that individuals make of their surrounding space depend on their perceptual and motor representations of their own bodies. For instance, how a person evaluates an object or an environment might depend on his virtual body position and movements. Embodiment in VR might be defined as follows: embodiment toward a body is "the impression that arises when a virtual body's features are assimilated as if they were one's own biological characteristics" [Kilteni et al., 2012a]. This definition was given in 2012, but nowadays, there are still discussions around this topic. Embodiment can be decomposed into three different dimensions [Kilteni et al., 2012b]:

- Ownership: the sense of ownership can be explained as the feeling that the represented body is one's own body and where sensations happen.
- Agency: the sense of agency is the feeling of having motor control in the virtual environment.
- Self-location: corresponds to the perceived location space of one's body.

Several works have focused on studying each individual dimension of embodiment in VR for different users' 3D representations and observing the users' experiences and behaviors in VEs. Other researchers have focused on the impact of embodiment on learning, distance estimation, and object-size perception in VR [Ogawa et al., 2019, Mohler et al., 2010, Ossmy and Mukamel, 2017].

Concerning the assessment of embodiment, several works have tried to determine the most appropriate metrics (e.g., subjective evaluation questionnaire, stimuli reaction). However, its definition is still not standardized since no consensus has been reached. In summary, the concept exists, but more research is needed to fully define, characterize its effects and determine the appropriate way to assess it [Kilteni et al., 2012a, Peck and Gonzalez-Franco, 2021].

Collaborative Virtual Environment Initially, VEs were considered a tool that could be used by only one user at a time. Today, however, VEs can be shared, allowing different users to be in the same VE simultaneously, thus extending VR to a multi-user tool. In this view, collaborative virtual environments (CVE) are a research topic attracting strong attention in recent years, especially following the Covid-19 pandemic and the need to work remotely through CVEs. CVEs' possibilities in terms of usage have been explored by researchers [Hrimech et al., 2011] who compared different interaction metaphors, highlighting the possibility of using such environments for collaborative work. A key point for successfully designing a multi-user VE is modelling users' avatars (e.g., by using a humanoid representation or a symbolic one), allowing them to feel the partners' presence, location, and orientation [Benford et al., 1997]. Some research questions arise concerning users' representation for CVEs, how to know if the avatar with whom we communicate/collaborate is the right person, and whether the person is actually present behind the screen without having to ask explicitly.

Different platforms already provide collaborative virtual environments. For example, "MASSIVE" is a conferencing system that uses simple boxes shape avatars with names and colours. "DIVE"[6] is another collaborative application which allows multi-user interaction and communication but uses a more realistic avatar representation, on which users can use a photo as a face. It is also possible to link a web page to the avatar leading to the owner's description and helping the introduction and identification of the speaker. Recently, and due to restrictions imposed by the Covid-19 pandemic, several education institutions and conferences proposed using CVEs to allow learners and presenters to perform traditional classes and exhibitions through virtual environments. For instance, the "Laval Virtual" exhibition proposed the use of a desktop application[7], which uses a simple avatar that the owner can customize. Other examples of massive virtual collaborative environments are "Horizon Worlds"[8], "Mozilla hubs"[9] and "Spatial"[10]. All these applications allow users to participate in online meetings with a virtual representation of themselves, as pictured in Figure 1.9.

Figure 1.9: Collaborative virtual environments. Left: iLRN Virtual Campus. Right: Mozilla Hubs.

[6] https://www.letsdive.io/
[7] https://www.virbela.com/solutions/open-campus
[8] https://www.oculus.com/horizon-worlds/
[9] https://hubs.mozilla.com/
[10] https://spatial.io/

Avatar and social skills Avatar representation, which is often part of embodiment and CVE research, faces different challenges, such as acquiring users' motion and facial expressions, animating and controlling 3D users' representations in real time, or providing realistic sensory feedback to the user. Creating a realistic and faithful avatar is a challenging and resource-consuming task. Moreover, having a high-fidelity avatar could heighten the user's expectation and thus be disappointed if the avatar does not react as expected, leading to the well-known uncanny valley effect [Lugrin et al., 2015, Yee and Bailenson, 2007]. Users can adapt their behaviour according to their own and others (i.e., partners in CVE) virtual representations. Several studies found that users tend to get closer and give more information to an attractive avatar, while being in front of a tall avatar will lead them to accept unfair deals easily (i.e., feeling intimidated). On the other hand, a simpler approach would be to represent the users with a simple avatar that the owner can customize. This simple customization could be enough to lead to a good sense of ownership [Jo et al., 2017] for some activities such as exhibitions.

The usefulness of VR tools for social skills is still debated among researchers, and some argue that the currently achieved fidelity of the avatar already allows users to train themselves [Howard and Gutworth, 2020]. Others argue that VR cannot be suitable for such training because social skills require subtle facial expressions that are not currently reproducible by technology. During daily communication, body representations allow us to support verbal communication but also to communicate more information, such as surprise, anger, fear or impatience. As the role of our bodies in everyday communication is essential, some researchers tried to find if VEs are usable to learn social skills or to study social behaviours [Benford et al., 1997, Jo et al., 2017, Park, 2018, Yee and Bailenson, 2007].

1.1.4 Hardwares (HMD/CAVE/Smartphone)

We dealt with different devices offering the possibility to enter a virtual world. In the following section, we present and define these different devices.

Head-mounted display A head-mounted display (HMD) (or VR headset) is a display device with a compact display optic in front of each eye that is worn on the head. In order to provide an immersive and interactive audiovisual experience, a VR headset incorporates stereo sound, sensors, and appropriate controllers. Due to its nature, when users wear an HMD, they can no longer see the world around them, only the VE projected, thus being cut from their surrounding physical environment. To interact in the VE, users rely on the controllers and interactions or navigation methods provided by the application.

Current HMD can be defined with four different basics features:

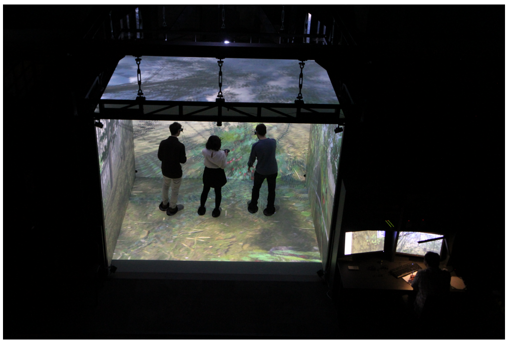
- **Six degrees of freedom** (DoF), achieved through sensors such as gyroscopes, accelerometers, and a 6-DoF system that tracks head movements and repositions the display accordingly.
- **Lenses and screens**, equipped with stereoscopic lenses that distort the image into appearing three-dimensional, the optic displays devices might be cathode ray tubes (CRT), liquid-crystal displays (LCDs), liquid crystal on silicon (LCos), or organic light-emitting diodes (OLED).
- **Immersive audio**, a stereo or binaural audio system is embedded in every HMD.
- **controllers**. Various controllers can be used, from single joysticks to data gloves, which allow users to interact within the VE.

There is currently a large offer for HMD devices, with a wide price and specification (e.g., refresh rate, resolution, FOV) range. We can find Oculus, HTC, Samsung, Sony, Google and Acer among the most important manufacturers.

CAVE systems CAVE Automatic Virtual Environment (CAVE) systems are defined by a set of wide screens equipped with tracking systems which allow applications to provide consistent viewpoints in the virtual environment according to the users' head rotations and movements. Due to its uncommon characteristic technology, which is expensive compared to HMD solutions, there are fewer manufacturers of this category of hardware. All CAVEs share the same basic structure. Commonly at the state of the art of the current technology during their design, from computers specification to projectors and screens, a CAVE is composed of two to six walls on which 3D stereoscopic images are displayed. Users wear glasses with trackers, allowing them to move in the VE with the correct viewpoint following their movements. Once in the CAVE with the glasses, users can see 3D objects around them and turn freely, like in real life or with a helmet. Dulina and Bartanusova [Dulina and Bartanusova, 2015] gave a workflow of the different settings to work on and proposed some reflections about creating CAVE devices.

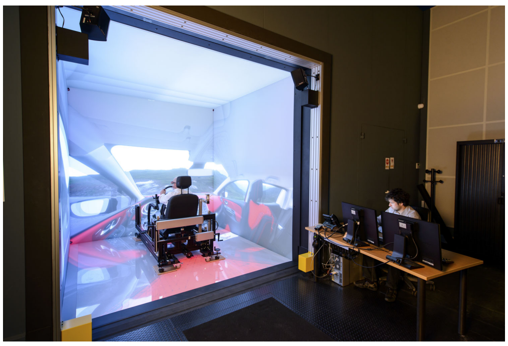
A whole spectrum of devices are labelled as CAVEs but are noticeably different from each other. For instance, some have wide screens arranged side by side, forming a horseshoe shape. Others are like corridors, with wide curved screens, or box-like with two to six sides. These differences in the structure of these devices may impact the interpretation of past studies' results involving CAVE systems and make it difficult to compare results.

Figure 1.10 illustrates several examples of different CAVE systems. For example, the Arts et Métiers Institute of Technology's *"BlueLemon"* is a cuboid composed of five screens measuring 3.40m (W) $\times$ 2.70 m (H) $\times$ 3m (D) with a double monoscopic viewpoint capability. The IFSTTAR's (now Gustave Eiffel University) *"immersive simulation rooms"* [Mallaro et al., 2017] is composed of ten wide screens arranged in a row for a total length of seven meters. The *"Mihriad"* is a desktop-size CAVE developed by Basset and Noël [2018], while the *"IRIS"* installed at Renault, France, is a five-screen CAVE system with 4K resolution.



(a) BlueLemon

(b) Mihriad



(c) IRIS

(d) IFSTTAR immersive room

Figure 1.10: Different CAVE systems

Technical specifications: Screens. The "walls" or screens are made with different materials, such as glass, plastic or fabric. Their dimension and number are managed depending on the size and space available for the CAVE system and future utility. Moreover, the screen type could be influenced by the projectors' technology or the other way around. For instance, if using passive projection (for older versions), specialized silver screens may be required. Furthermore, different layouts for hardware are possible, such as using mirrors between the projectors and the screens to avoid the user's shadow being projected, bright or dazzling lighting, and according to space available for the CAVE installation as described by [Dulina and Bartanusova, 2015]

Projectors / Glasses. Lighting is either direct or indirect using reflecting mirrors (usually made of polished sheets). In both cases, the most critical and challenging part is avoiding overlapping images, which might happen on the edges of the CAVE's different screens. Moreover, the luminosity should be carefully set to avoid dazzling. The type of projectors must be chosen regarding the technologies to be used and the budget available. Two technological choices are usually proposed to provide stereoscopy in a CAVE system. "Active projection" [Company], the cheapest technology, relies on specific glasses usually made with liquid crystal and on projectors capable of displaying at least sixty frames per second. The glasses quickly alternate between black and transparent to allow each eye to see a different picture. The second technology is "passive projection", for which the projector shows two images simultaneously, differentiated by either polarization (i.e., light wave) or spectral decomposition (i.e., light colour).

Tracking. The tracking system comprises all the components allowing user tracking and image adaptation. Tracking can be led by mechanical, magnetic, optic, infrared or ultrasound techniques, the latter three being the most widely deployed. Tracking devices are usually positioned at the edges or corners of the screens to avoid being seen in the 3D visualization. If not perfectly calibrated, the user may notice overlapping or holes in the 3D environment, leading to a break in the immersion.

Interaction. Similarly to HMDs, devices such as controllers or wands can be used to allow the user to interact with the VE. Image recognition for hand tracking or gesture recognition can also be considered. The different systems usable with HMDs are generally functional within CAVEs.

Smartphones The last device allowing to immerse a user in VEs is a smartphone. Mock-ups or cardboards can easily be found folded, allowing to transform recent smartphones into HMDs. In fact, the number of possible specifications is vast, making it difficult to give an in-depth overview. Indeed, some mobile phones have been offering this possibility for years, and every month new models come out to the general market. Although these devices can offer a cheaper way to access VEs, they present various disadvantages, such as the lack of interaction, low rendering capacities and poor graphic quality. At last

1.2 Interaction in Virtual Reality

1.2.1 Introduction

In the previous sections, existing devices allowing VE display were presented. In the following sections, the different ways to interact in VEs are listed and explained. Moreover, a discussion concerning the conflicts of visualization systems with human visualization is also presented. Those conflicts might provoke uncomfortable effects in the users, i.e., cybersickness. The last section focuses on presenting cybersickness, particularly its symptoms, and how to assess and rate it. Following [Peukert et al., 2019] point of view, information systems are mainly based on two paths, the "hedonic" path, which focuses on self-fulfilling and fun-aspect and encourages prolonged use, and the "utilitarian" path, which promotes productive use and focuses on tasks and efficiency. Therefore, finding the best way to manage those two paths is crucial and mandatory. In this way, an application designed to be purely informative will not be particularly fun, and a purely entertaining application is rarely the main objective, except for the entertainment industry. To encourage both paths, there are different technologies which stimulate humans' primary senses. Even if it seems like paths go in opposite directions, each can enhance the other. It is worth noting that, according to [Zhang, 2017], visual sense takes 70% of the human being, against 20% for auditory, and 10% for smell (5%), touch (4%), and taste (1%) senses. Therefore, by involving vision and auditory resources, we usually stimulate the two most important senses, which is important to consider when developing VR applications.

1.2.2 Interaction with objects

To interact through virtual environments, thanks to a CAVE or an HMD system, there are two main groups of interaction [Muhanna, 2015]. The first one is the **object-action** group, where the user selects an object and then interacts with it. The object with which the user interacts could be determined by first pointing/selecting the object (e.g., through a ray casting technique). This could be achieved by using controllers or user gaze detection. The second way to interact is the **direct interaction**. This metaphor is closer to reality. Indeed, the user can interact directly with objects using controllers or hand detection. The metaphor chosen to interact with objects depends on the application's purpose and possibilities. It might always seem better to use the second interaction group. However, for some tasks, such as selecting little objects (e.g., screws or thumbtacks) or selecting objects far from the user's position, the first metaphor could be more appropriate.

Furthermore, action control can be differentiated into four types. Following the study of [Bozgeyikli et al., 2019].

Direct action, where the user uses gestures and gaze to interact with the virtual environment without any additional devices. This is the closest to real-life interaction since it relies on gesture recognition and gaze tracking to be implemented without the need to add devices.

Physical control allows interaction within the application using objects as devices. The devices could be a pick-axe [Tcha-Tokey et al., 2017], a wand, gloves, an extinguisher, or almost everything the application needs.

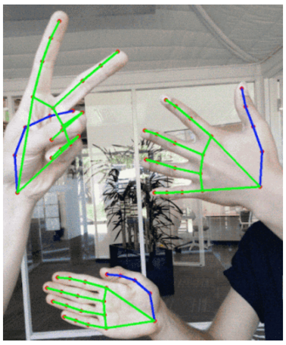
Virtual control is close to physical control except that the device used is not real, existing only in the virtual environment. It allows interaction with the virtual environment inside it, for instance, a light switch, sink tap or electric shutter.

The last type is an indirect interaction, **agent control**, which are the interactions made through another entity, which can be a human or a computer, to whom we will ask something (e.g., through voice or gestures). These four interaction methods are depicted in Figure 1.11.

1.2.3 Movement within the virtual environment

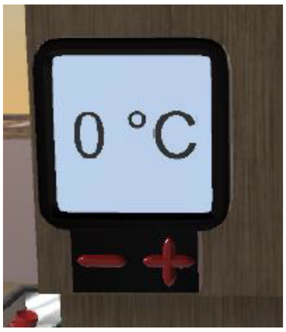
Navigation in VR is a fundamental feature. Indeed, immersive systems generally take place in a restricted physical area, thus limiting real movement to some meters around the user. If the application requires the user to move within the VE, a navigation method must be implemented, and many different possibilities have been explored. Different studies investigate locomotion methods in VE [Bozgeyikli et al., 2019, Drogemuller et al., 2020, Boletsis, 2017]. Hereafter, we present a summary list of state-of-the-art navigation techniques which allow users to move in VEs.

Redirected walking: It consists of rotating the environment during the application so that the user walks in a circle-shape in real life, while in the virtual world, he/she moves straight-forward. When



(a) Direct action

(b) Physical control



(c) Virtual control

(d) Agent Control (AstroBot)

Figure 1.11: Four different interaction controls

using it, special attention must be paid to the redirection speed. Indeed, if it is not set correctly, the user might notice the redirection, or he/she might reach the room's corners despite the redirection.

Walk-in-Place: This metaphor is meant to simulate the walking movement. Participants will simulate walking by mimicking it but without actually moving. It helps reduce cybersickness.

Stepper machine: A stepper is an exercise machine which simulates an uninterrupted "climb up the stairs" metaphor. It brings a sensation closer to the walk-in-place metaphor, but according to a recent study [Bozgeyikli et al., 2019], it may be exhausting to use it for a long time.

Point and teleport: These techniques have the advantage of being easy to manage and relatively quick to understand. There are two different implementations, using fixed points or free area setup. The first one locks the user in specific tracks or viewpoints and might be helpful to limit the users' interaction and navigation and guide or "force" them to see and pass through specific locations. The second one allows users to go anywhere; therefore, it better fits full exploration tasks and allows users to make their own path choices. Teleport might also be carried with the ”world in miniature”, the user can see a reduced version of the VE and decide where to go by pointing to a specific location, this allow the user to see a complete representation of the environment.

Flying/Joystick/Trackball/Hand flapping: From the developer's point of view, this solution is the easiest to include and manage in VR applications since most of the engines already implement these features. Through these techniques, users "slide" in the VE using different controller types, making some movements more or less easier according to the controllers used. Indeed, joysticks or trackpads induce better movement speed and are quick to operate for users. However, these techniques are prone to cause more cybersickness, mainly because users tend not to have a smooth displacement due to non-voluntary movement, acceleration, stop, or collision.

Gogo-Hand: This technique uses the interaction metaphor of an extended hand [Poupyrev et al., 1998], and it was implemented to allow interaction with distant objects. This metaphor can also be used for navigation: users can "grab" a point far from them and pull themselves to that point.

Navigation techniques comparison

Many studies compare the pros and cons of each navigation metaphor, either to explore a vast virtual environment or a smaller one. Some might induce more cybersickness than others, and there is no perfect global navigation technique. Depending on the environment, some metaphors are more efficient [Coburn et al., 2020]. A study which compared four different navigation techniques concluded that fly and manual navigation techniques allow participants to be aware of their position in the VE, while fading and teleportation tend to lose them. Nevertheless, no metaphor was unanimously accepted by users. Table 1.2 presents a comparison of the different means for locomotion in VE. We made this comparison according to five characteristics: the easiness for users to understand and use the technique ("ease of use"), the users' physical demand ("Exhausting"), the possibility to cover long distances ("fast travel"), the convenience to explore narrow environments and/or with obstacles ("Accuracy"), and the propensity to cause cybersickness ("Cybersickness").

1.2.4 Other ways to interact with virtual environments

Visual control (gaze directed)

There exist different ways to involve the user's gaze in VR since, thanks to sensors, it is possible to know where the user is looking at. Thereby, the user's gaze can be used to display information

Table 1.2: Navigation techniques comparison

	Ease to use	**Exhausting**	**Fast travel**	**Accuracy**	**Cybersickness**
Redirect walking	++	+	- -	++	+
Walk-in-Place	+	+	-	+	++
Stepper machine	+	+++	-	+	++
Point & teleport	- -	- -	+++	+++	-
Flying	-	+	+	-	+++
Gogo-Hand	+	-	++	++	+
World in miniature	+	- -	+	- -	-

depending on where he/she is looking (e.g., showing information about a monument if the user is staring at it). We could use this same metaphor to change the scene or point of view (e.g., we can imagine moving closer to the monument). To prevent the user from going to every point of interest they look at, a countdown timer usually differentiates the user's wandering gaze from an actual point of interest they want to reach.

Brain-Computer Interfaces

Brain-Computer Interfaces (BCI) allow users to interconnect the brain and computers, allowing them to send instructions to the computer according to their brain activity. Initially, BCIs were developed to communicate or control devices for people with severe disabilities. In parallel, VR has gained considerable interest as this technology can fully stimulate the brain. Moreover, it is also accessible for people that are sometimes unable to move in other realities/environments. VR devices are helpful and work great to help patients recover through specifically designed scenarios and interactions. A study in 2020 [Leeb and Pérez-Marcos, 2020] investigated the use of BCI for neurorehabilitation. The first is based on voluntary actions from the participant (i.e., the user thinks about walking, thus his/her avatar will walk), and the second is based on reactions to stimuli.

1.3 Perception in virtual reality

Previous studies show that conflicts exist between the vision in real life and inside a virtual environment. In particular, a constant distance and height underestimation in VR setups has been noticed. According to the review of thirty-three articles made by Kelly et al. [Kelly et al., 2017] the average underestimation is 73% of the actual size. Moreover, VE is often associated with virtual sickness (i.e., cybersickness) due to visual-vestibular conflicts. These conflicts could lead to visual disorders (e.g., hallucinations, eye strain and blurred vision), dizziness and headaches, fatigue, pallor, sweating, gastrointestinal disorders (i.e., the compression of the upper abdominal cavity, nausea, emesis, or loss of appetite), apathy, limited mental concentration and muscular activity.

Some studies compared differences between real and virtual environments to assess which points or specifications affect our visual system [Renner et al., 2013, Marsh et al., 2014]. The question of the veracity of our distance or size estimations regarding a virtual environment emerged with the invention of new technologies, such as HMDs and CAVEs. Indeed, with those devices, the initial goal is to bring up to the user a close representation of real life, thus reaching an equal (rather comparable) representation. However, before immersive 3D displays, the environment (virtual here) was not observed (e.g., through 2D displays) with the expectations of it being real (i.e., the question of real representation did not arise). In fact, compared to movies, viewers accept the camera's point of view without asking how they could physically have this one. Whereas, when using VEs, the viewers have a personal point of view to which they can pay attention in detail. In addition, as previously stated (see Figure 1.1.2), VR tools are used for education, learning and product review, thus making an accurate representation and allowing to have comparable (to real life) experience, a foremost objective.

1.3.1 Differences between virtual and real environments

Issues due to eye functioning Convergence, accommodation and motion parallax are accurate measurement methods for short-distance in real environments [Renner et al., 2013, Ghinea et al., 2018]. Whereas, in virtual environments, the screen biases those visual cues in either CAVEs or HMDs because the object and its picture are not on the same visual level. Indeed, the object's position may vary according to the screen position. For instance, in a CAVE, an object far from the user will be displayed behind the screen. Therefore, if the user moves the viewpoint towards this particular object until he/she can grab it, at some point, the object will be on the screen, and then it will be between him/her and the screen as illustrated in Figure 1.12. This may lead to different convergence/accommodation conflicts. Indeed, the eyes will focus on the screen (i.e., the real object that displays the virtual environment) while the brain sees the object closer or further in space. Eye convergence works with short-distance objects, while our accommodation works with long-distance [Vienne et al., 2020] ones. In the case of HMDs, this leads to conflicting depth information, which may lead to visual fatigue and possible cybersickness. In addition, it has been specified that vergence-accommodation mismatch is a major difference between real-world visualization and visualization through stereoscopic displays [Lipton, 1982].

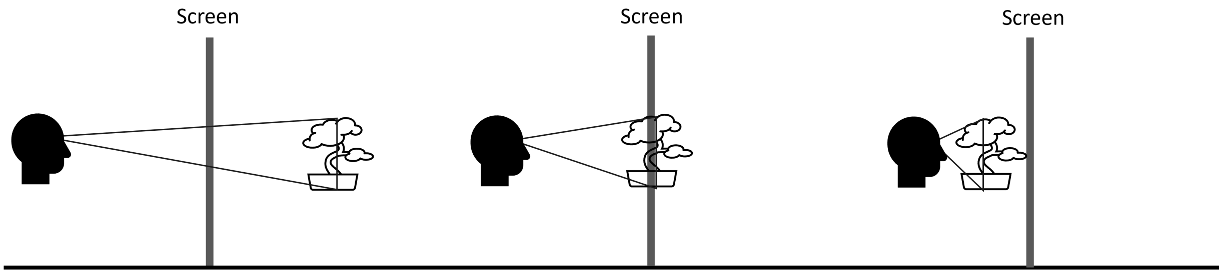


Figure 1.12: Three different rendering positions with a CAVE display

Issues due to the technology setting *IPD:* The interpupillary distance is the distance between the user's pupils. With recent HMDs, it is adjustable to fit each user. In fact, a lousy adjustment of this setup will induce distance misestimation and may increase cybersickness symptoms [Renner et al., 2013, Vienne et al., 2020].

Resolution With HMDs, it is (still today) hard to comfortably read texts [Peukert et al., 2019], mainly due to the display resolution. Even with the "HTC Vive PRO Eye", which is an advanced HMD, pixels are still visible. Therefore, until the technology improves, research suggests making the text thicker or enlarging text when users pick up objects containing text. Even if it is less realistic, it will allow users to read it or see details. Moreover, if done well (i.e., slight modification), users could hardly perceive this.

Screen curves Additionally, the curvature of the HMDs' inside lenses has proven to induce a barrel effect (see Figure 1.13) in the image, leading to a picture minification and, thus, to distance misestimation [Kuhl et al., 2006, 2009]. This effect usually does not occur with CAVE systems, as non-curved screens characterize most of them. To compensate for the barrel effect, we could proceed as follows: above the distortion effect on the image depending on the screen curves (here a barrel effect), apply an anamorphosis effect on the picture, prior to displaying it into the HMD [Durgin and Li, 2010].

Vestibular conflict When using VR applications, there are multiple sensory mismatches between different sensory systems. The visual system will send movement information, while the internal ear

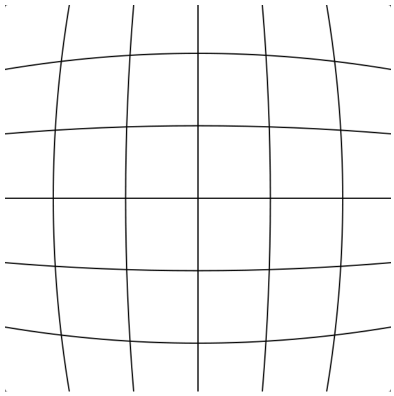


Figure 1.13: The barrel effect

will send information about a static position. The conflict between the two sensory systems is the most cited and accepted theory to explain motion sickness [Ng et al., 2020]. It is the fundamental cause of all motion sickness, a mismatch between perception and the vestibular system. The user's age effect may also increase the impact of this mismatch [Jinjakam and Hamamoto, 2012]. Indeed, the older the participant, the more prone he/she is to experience simulator sickness, which may originate from the increasing balance and dizziness issues of getting older, or that the younger generation is usually more accustomed to screens and new technologies.

Cybersickness is further investigated in the next section due to its primary importance in the development of VR applications and of particular interest in our subject of study: the impact of displays' characteristics on user experience.

1.3.2 Cybersickness

Definition and Impacts of Cybersickness

Definition: There are several ways and techniques to rate participants' immersion, perception, presence or well-being after and during an VR exposure. Some of these ways are objective (i.e., based on physiological measurements, thus participants cannot be wrong or misinterpret their symptoms, and it is more complicated if not impossible to influence those outputs) like heart rate, skin conductance or skin temperature, and some of them are subjective (i.e., strongly linked to participant feeling, it can change between participants and among them between two sessions), such as questionnaire, verbal estimation and verbal feedback. Cybersickness has much impact on users' experiences. Participants are often attracted by new technologies, but cybersickness may prevent them from reusing it [Somrak et al., 2019]. Symptoms are the same as the motion sickness symptoms: nausea, pale skin, cold sweats, vomiting, dizziness, headaches, salivation and fatigue [Rebenitsch and Owen, 2016]. However, they are not rated at the same level; if separating the oculomotor, disorientation and nausea as previous studies recommend, each different motion sicknesses (sea-sickness, space-sickness, cybersickness) induces different responses (i.e., sea sickness causes more nausea than cybersickness). The effect could appear after hours of use but also after minutes. It is commonly accepted that the main reason for those effects is the sensory mismatch between different vestibular systems [Rebenitsch and Owen, 2016]. Motion sickness might come from three main conflicts [Kim et al., 2018]: 1) what I felt but did not see, 2) what I saw but did not feel, and 3) what I felt but did not match what I saw. Simulator sickness usually mainly originates from conflict two. It is possible to divide impacts and measures into two families: on the one hand, the physiological family, which belongs to body responses, like heart rate, skin conductance, skin temperature, sweat, and saliva, based on physiologic measurements. On the other hand, the psychological family, those measurements tend to be more subjective and can vary according to participants' moods or feelings; questionnaires, verbal estimation or feedback. It is worth noting that cybersickness effects are polysymptomatic (i.e., multiple symptoms) and polygenic (i.e., differ depending on the individual).

Impacts of cybersickness Cybersickness causes several adverse effects, effects that can be very different. The following is an exhaustive list of symptoms induced by exposure to virtual reality. As already mentioned, those symptoms are close to motion sickness but on a different scale [Malińska et al., 2015, Rebenitsch and Owen, 2016].

- Nausea
- Pale skin
- Cold sweats
- Vomiting
- Dizziness
- Salivation
- Fatigue

- Eye strain
- Blurred vision
- Gastrointestinal disorders
- Apathy and limited mental concentration and muscular activity

Time spend in virtual reality seems to influence cybersickness symptoms significantly. An impressive study of Steinicke and Bruder in 2014 [Steinicke and Bruder, 2014] asked one participant to stay for twenty-four hours in a VE (eleven blocks of two hours with ten-minute breaks); during the VE exposure, real objects position were matched with virtual objects such as a bed, chair, or desktop, in that way, the participant was able to interact with object and live in the VE. During each break, they took the participant's picture and asked him to answer different questionnaires such as SSQ, SUS and comfort on a Likert scale; surprisingly, the cybersickness level was low compared to the time exposed. However, at the end of the experiment, the participant was confusing the real and virtual world and suffered from dry eyes; he noticed that a comfortable pose reduces simulator sickness.

Psychological measurement

Psychological measurements are easier to carry because they do not require additional data collection devices. They are often questionnaires elaborated for specific purposes, questions or discussions with participants. Some of them have been proved efficient in assessing cybersickness level. However they could be pretty long and tedious for participants to fill up. Forms are often composed of statements on the well-being at the very moment; thus, it is frequently asked to fill the form multiple times along with the experiment; due to participant differences and the self-evaluation nature of the questionnaires, it can be strongly influenced by external factors, such as sex, age or current mood. Thus, we present different questionnaires that have the function of assessing the cybersickness level.

MSQ (Motion sickness questionnaire) The "father of all motion questionnaires", the first related to motion sickness, the following questionnaires are a direct result of this one. It was designed for transport sickness. Four dimensions of motion sickness have been identified: gastrointestinal, central, peripheral, and sopite-related. Thereby, further studies modified this one and created more specific questionnaires. The different motion sickness involves the same four dimensions/symptoms.

SSQ (Simulator Sickness Questionnaire) It is an enhanced version of the motion sickness questionnaire (MSQ). Indeed, SSQ is a variation of the MSQ but dedicated to simulator sickness [Kennedy et al., 1993]. SSQ identifies three main symptom categories: Nausea, Disorientation and Oculomotor, with a more general factor: total severity. They kept sixteen symptoms from the MSQ, since some symptoms assessed in the MSQ are never reported with simulator exposure. It has the disadvantage of being long and primarily developed for a military population. However it is still widely used by different studies to assess cybersickness levels [Rebenitsch and Owen, 2016, Bruck and Watters, 2009]. This needs to be assessed before and after the simulator exposure to compare changes between both scores.

VRSQ (Virtual reality sickness questionnaire) SSQ has been modified to fit cybersickness. Some items from the SSQ are irrelevant to assess cybersickness. To elaborate this form, Kim et al. [Kim et al., 2018] rate the impact of each SSQ item before and after exposure to a virtual environment, and they purposely remove the items that are not significantly impacted by VR exposure. Thereby they retain only nine symptoms compared to the SSQ.

MSSQ (Motion Sickness Susceptibility Questionnaire) Revised Motion Sickness Susceptibility Questionnaire (MSSQ) by [Golding, 1998], they created it to have a shorter questionnaire to assess motion sickness, they argue that even with less items, the results are reliable.

SUDS (Subjective Units of Distress Scale) This questionnaire is shorter than the SSQ, it has been proved efficient in assessing sickness levels according to [Somrak et al., 2019, Guna et al., 2019].

POMS (Profile Of Mood Stat) It assesses the current state of participants mood, it is a quick questionnaire to carry. Composed of forty Likert scale questions, divided into subcategories: Tension, Anger, Fatigue, Depression, Esteem-Related-Affect, Vigor and Confusion [Grove and Prapavessis, 1992].

FMS (Fast Motion Sickness Scale) This questionnaire is composed of one simple Likert scale question, thus it is rapid to carry, and author claim the reliability to assess cybersickness [Rebenitsch and Owen, 2016].

MISC (Misery Scale) As the FMS this questionnaire is composed of one question, see Figure 1.14, according to the author it is also reliable to assess cybersickness [Bos, 2015, Bos et al., 2010].

SUXES This questionnaire was developed to analyse user expectations and experience. The service quality metric questionnaire called SERVQUAL was adapted to fit new technologies [Turunen et al., 2009]. Participants must respond first to a statement before the experiment, and they need to put two marks, their expectation and the acceptance mark. After the experiment, they have the same questions, but this time they fill with their experience. As a result, each participant has three marks for each item, acceptance, expectation and experience. Allowing to get the Measure of Service Superiority (MSS, i.e., the difference between perceived level and desired) and the Measure of Service Adequacy (MSA, i.e., the difference between perceived and accepted).

Warning The main issues with questionnaires, verbal feedback or discussion with users are that it is impossible to carry them during the application, it asks participants to leave the virtual environment to answer, and therefore reduces their immersion. Also, because it is based on people's sensitivity and honesty, differences might appear depending on participants' background or personality; for instance, between men and women; men will tend to hide their symptoms, thus ranking a lower questionnaire score [Rebenitsch and Owen, 2016]. While creators of questionnaires explain that their questionnaire are reliable, past studies show that SSQ and FSSQ did not reveal evidence of usability compared to VRSQ and the Cybersickness Questionnaire (CSQ) [Schneider and Bengler, 2020].

Physiological measurements

Physiological measurements allows objective data about users' experiences, limiting any bias from the user's personality or background. Physiological feedbacks give information about the user's well-being during the application. If users face cybersickness, it will prevent them from getting immersed

Symptoms		MISC
No problems		0
Some discomfort, but no specific symptoms		1
Dizziness, cold/warm, headache,	Vague	2
stomach/throat awareness, sweating,	Little	3
blurred vision, yawning, burping,	Rather	4
tiredness, salivation, ... but no nausea	Severe	5
	Little	6
Nausea	Rather	7
	Severe	8
	Retching	9
Vomiting		10

Figure 1.14: Misery scale question [Bos, 2015]

and enjoying the experience. Moreover, physiological measurement methods usually interfere less with participants' experimentation since there is no need to interrupt immersion to fill out forms or answer questions, and they can be carried out during the experiment, thus allowing continuous measurement. Even if they seem more reliable than forms, it is essential to remember that some of these physiological measurement methods, if not all, can be influenced by the participant's physical background. If a participant runs every day and one other barely does not do any activity, their heart rate will not behave similarly (e.g. participants who like adrenaline sports activities are less affected by simulator sickness).

Heart-rate Heart rate (HR) is a common and easy way to assess the user's cybersickness level [Malińska et al., 2015, Bruck and Watters, 2011, Dużmańska et al., 2018], easily evaluated with a small device like a watch or small sensors, it can be carried during the experiment. HR also has the advantage of being easy to interpret; if the HR increases, it is likely that the participant is suffering from cybersickness or at least feeling unwell, as in Figure 1.15, for a participant who experienced discomfort during experimentation. However, HR is quite sensitive; some other factors can influence it, such as the stress of experimenting (e.g., if the participant is nervous about new technologies) or the weather (high temperatures increase HR). Thus it is interesting to control these factors as much as possible. It is common to control room temperature, check HR before the experiment, and explain the whole experiment process and goal to the participant. Moreover, because of individual differences, HR is usually compared within participants; indeed, there is no standard HR.

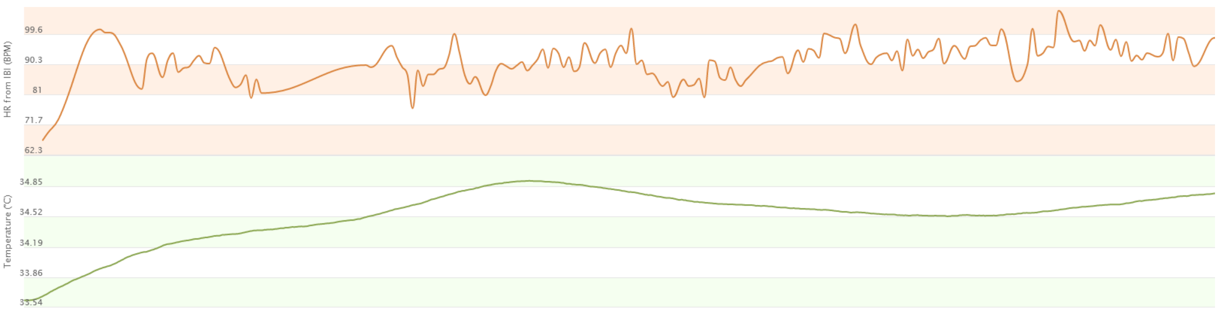


Figure 1.15: Participant's heart-rate and temperature during a VR experiment

Electrodermal activity Electrodermal activity (also known as skin conductance - SC) consists of the electrical characteristic evaluation of the skin. It is strongly linked to the cybersickness level too and it is a reliable way to assess it [Guna et al., 2019, Rebenitsch and Owen, 2016, Dużmańska et al., 2018]. Hardware to access this measure is available to the public market but is more complicated to get than HR hardware and is usually expensive. Data collected through SC need knowledge about the sympathetic nervous system to understand, analyze and interpret the outputs. Figure 1.16 depicts the evolution of SC during VR exposure.

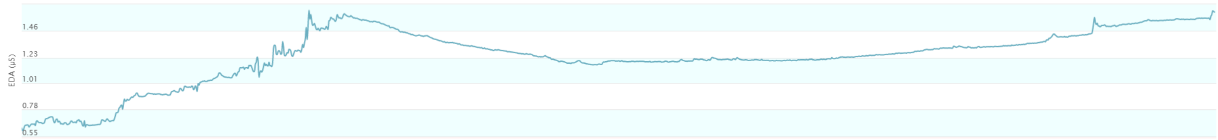


Figure 1.16: Electrodermal activity of the same participant during the same period of time

Postural stability Cybersickness might cause postural instability (PI), moreover, checking on it might also predict whether the user will experience sickness or not [Owen et al., 1998]. PI must be measured before and after the exposure. In fact, recent research [Arcioni et al., 2019, Sevinc and Berkman, 2020] have shown that postural instability is linked to cybersickness as illustrated in Figure 1.17 with pre and post PI depicted. Moreover, they highlight the usability of pre-test postural instability to predict the user's likeliness to experience VIMS.

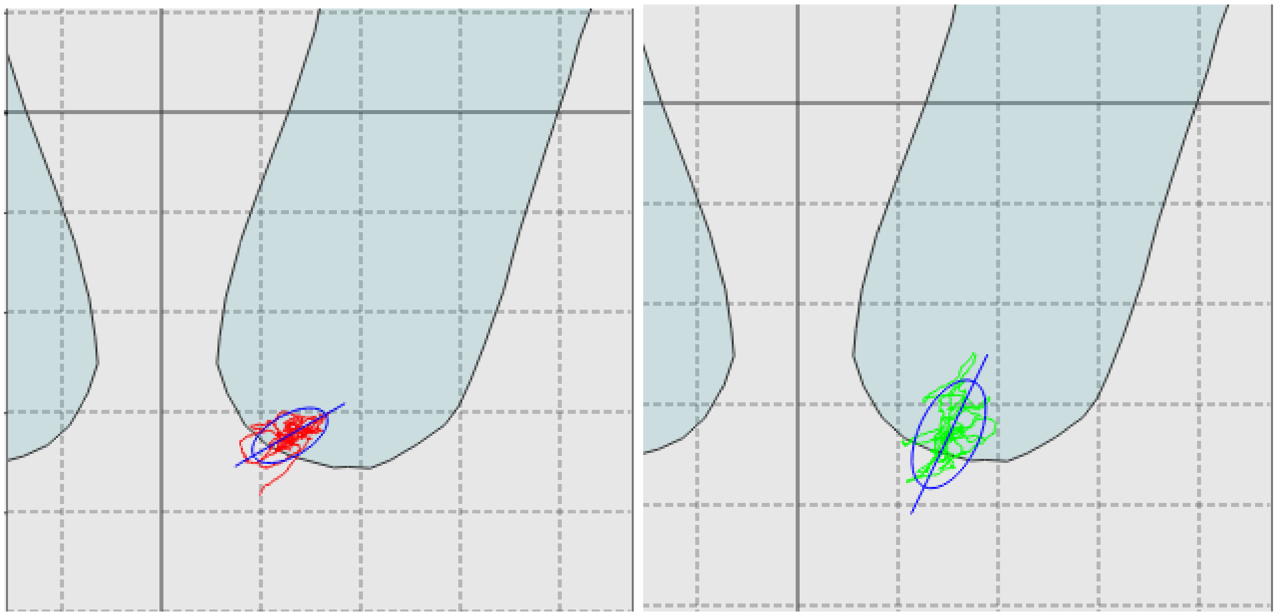


Figure 1.17: Postural stability before (left) and after (right) VR exposure. Top view representing the center of gravity during 13 seconds

Less common ways to assess cybersickness The following measurement methods are less used due to the price, difficulty to setting up devices, the inconvenience that this type of material can cause, or the complexity to analyse the data. **Forehead Sweating**: The forehead sweats may be useful to assess cybersickness, but this symptom disappears quickly and is hardly self-reported by participants [Schneider and Bengler, 2020]. **EEG**: Electroencephalography has been evaluated, and specific waves and areas showed good consistency and significant changes associated with VR sickness [Lim et al., 2021]. **Salivation**: Part of the questions in some simulator sickness questionnaires assesses the salivation level of participant, but there is no way to assess it without perturbing the participant. **Respiratory rate and electrocardiogram**: Thanks to relative small devices it is also possible to record respiratory rate, both can be linked to participant's cybersickness, however can both be disturbing for the participant.

1.3.3 User experience

Virtual environment factors When developing an application, the developer is able to manage every aspect of it; thus, for all the elements, questions arise: Is that useful? Why? How? and How could this feature influence the user's experience? Different elements influence UX; if the environment behaviour is natural (i.e., behaviours that are as close as possible to real-life), it is easier for the participant to feel immersed. Multiple studies have shown the usefulness of having a representation (i.e., an avatar) of the user in the virtual environment, which helps to increase the presence and also seems to help for a good representation of the environment scale. As an essential thing, there is the sound, allowing spatialization and increasing immersion [Dorado et al., 2017, Liu and Kang, 2018]. The brightness of the light or artificial sun also needs to be carefully set [Dorado et al., 2017] as the reflection of each material, still to avoid unrealistic visual effects, as depicted in Figure 1.18.

Interactions factors Two interaction types exist in a virtual application, the VE itself and the user toward the VE. The first one is usually fully supported by the software used for the application development (e.g., Unity, Unreal Engine, PolyVR), and even if it is allowed to modify it, all the basics behaviour are implemented, like physics, collision or light. The second interaction, VE with the user, involves different metaphors for the user to interact with the VE, interact with other users, or explore the environment, and as seen previously in section 1.2 there exist multiple ways to manage it.

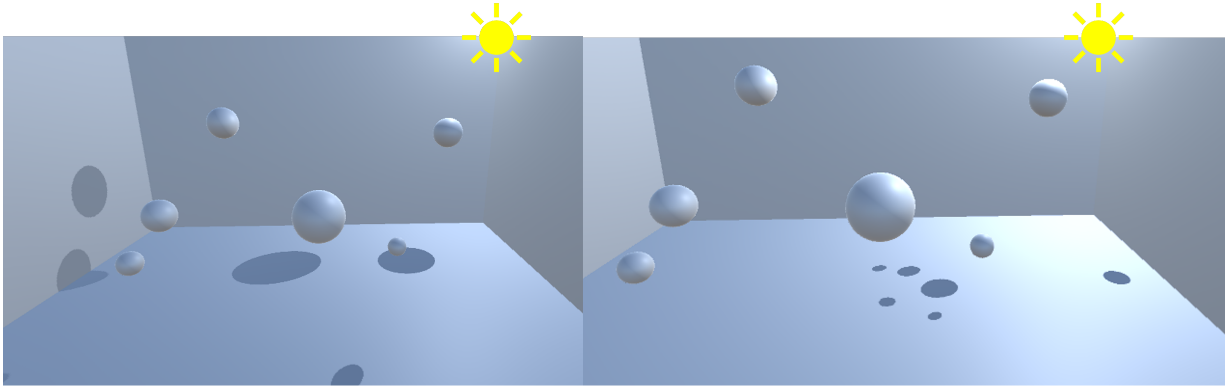


Figure 1.18: Light setting in virtual environments. Left: compliant shadows / Right: non-compliant shadows

Distance estimation factor Underestimated distance ratings concerning egocentric and exocentric distance and for object size evaluation under certain conditions have been studied by several researchers. An extensive literature review on this specific point have been made by Renner et al. in 2013 [Renner et al., 2013]. Multiple elements have been found, and various studies contradict each other. Some of the HMD characteristics could affect user distance perception, such as convergence, accommodation and motion parallax. By comparing three conditions, an unrestricted FOV, with an HMD mock-up and with an actual HMD, the following conclusion have been made: HMD itself cannot explain underestimation, but mechanical HMD factors such as the weight or the restricted field, moment of inertia or FOV could affect the distance perceived [Willemsen et al., 2004]. Screen distance still affects distance perceived for long distances even with additional motion parallax information [Vienne et al., 2020]. Comparisons between CAVE-like VR systems and HMDs revealed that accommodation-vergence conflict and inclusion of a rich environment were the influential factors impacting depth perception. However, display factors like luminance and resolution have little to no effect on depth perception, and the importance of eye-screen distances must be considered.

Influencing factors Users have some difficulty imagining themselves in the virtual world because the room they perceive in real life is different from the virtual one (e.g., a user switches from an office to a spaceship) [Interrante et al., 2006] . Thus, the brain cannot accept this new environment because of the sudden change, which makes the user feel more uncomfortable and may lead to distance underestimation and lack of immersion. **Participant background** may impact user sensibility to VR sickness, Rosa et al. in 2016 [Rosa et al., 2016] ran an experiment focusing on gaming background and according to their results and also supported by past studies, people with consequent gaming experience are less prone to have cybersickness symptoms. In contrast, people with low or no experience should pass through a familiarization process [Yildirim, 2019, Guna et al., 2019].

1.4 Conclusion

In this chapter, we first gave an overview of the history of VR, from the first devices allowing to enter VEs to the last generation of HMDs. We presented the different mainstream usage of these devices, which are mainly entertainment and edutainment. Some of the current research topics, such as avatar representation and CVE were also presented. We have gone through the different ways to interact in VR, whether it is to move, select objects or interact within the VE. Indeed, there exist many metaphors allowing users to do so. And finally, we have summarized the symptoms and methods to assess cybersickness. Both, psychological and physiological methods are employed, and each method has advantages and limitations. On the one hand, psychological methods can be biased by the participants but are easier to implement. On the other hand, physiological methods are more reliable, but the data must be analyzed with care, depending on the context of the experiment and the participant's background.

Chapter 2

User Experience and CAVE vs HMD

We have previously reviewed the history of virtual reality, presented definitions of key words (as they will be used in this manuscript), and the methods of interaction and perception that are possible or required when using virtual reality. In this chapter we will first present the user experience following the scheme proposed by [Stanney et al., 2003]. In this way, we will give a better understanding of what the user experience is and what can influence it. We will then return to the themes discussed in the previous chapter, but this time with our two devices as a lens. This will allow us to begin a comparison of CAVE and HMD. Finally, we will draw up a comparison of the systems, in order to highlight the differences that seem fundamental to us and that we will therefore try to analyse in our studies

2.1 The MAUVE method

No final or commonly approved guideline exists to develop an efficient, immersive, optimal VE system for CAVE or HMD. The first section is constructed following the classification given by [Stanney et al., 2003]. Their article proposes a list and classification of different points to care of while developing an application. Their method is called "MAUVE", which stands for Multi-criteria Assessment of Usability in Virtual Environment. It differentiates two main branches. The "VE System Interface", which is about the application side in terms of interaction, navigation, environment behaviour and graphics and the "VE user Interface", which is about the user feedback cybersickness and immersion, see Figure 2.1.

CAVEs and HMDs are two systems allowing to display, interact and explore virtual environments through different devices. However, these systems have clear distinctions and these differences may lead to dissimilar users' behaviour, users' immersion, or users' visualisation of the VE. Therefore, the development of the application might differ according to which device will be used thereafter. Also, HMDs and CAVEs do not aim for the same clients and purpose; while most HMDs are intended for personal use and mass sales, CAVEs are intended and built by research laboratories or companies for specific purposes. Therefore, in the first case, the build cost must be controlled and reduced, while in the second case, the built price is usually adapted to future usage. Then focus on the differences arising from devices' dissimilarity, such as the weight or the FOV limitation, is made.

Finally, we present our experimental approach made in order to answer the research questions. The fundamental differences chosen for the experiments are detailed here, as well as the associated literature review. The main differences between an HMD and a CAVE relate first to their hardware properties. The resolution, computer rendering capabilities, latency, the distance between eyes and screens, screen curvature, field of view and field of regard are among the differentiating factors that may influence user perception and immersion, independently of the applications displayed. It is therefore the targeted factors that have been explored in this work.

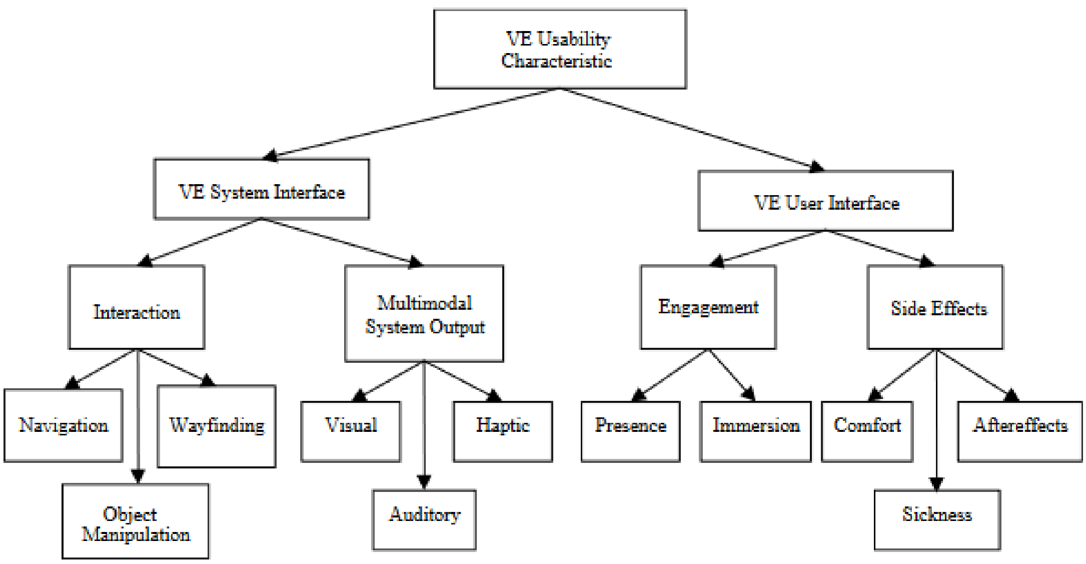


Figure 2.1: MAUVE [Stanney et al., 2003]

2.1.1 VE system interface

1. Multimodal system output

1.1 Visual

Resolution limitation [Guna et al., 2019] who compared a television, new and old HMDs and Mobile devices encourage to improve visual feedback. They found that new HMDs induces less cybersickness than old ones. It could mean that technological improvement will reduce cybersickness on its own. These results are also supported by the study of [Kelly et al., 2017] who studied different HMD generations and found significant improvement between old HMDs and recent ones. Regarding the task of reading texts in VEs, [Peukert et al., 2019] noted that even with a high-resolution HMD, it is a challenging task. Therefore, artificially enlarging elements to make them easier to read could be a satisfying solution for known objects since the user will understand that the size displayed is only here to serve the interaction. However, it is impossible to rely only on technological improvement to solve every issue due to HMD utilisation; the technological progress will only affect refresh rate, resolution, FOV, FOR and movement accuracy.

Screens The device calibration is often forgotten in studies; most studies did not mention if they calibrate the Interpupillary Distance (IPD), whereas, if not calibrated, it might influence experiment results, as it influences visualization. As seen previously, there exists a distortion due to screen curves (Figure 1.3.1), [Durgin and Li, 2010] proposed a solution which is to apply "pincushion correction algorithms"; they distort the image in the opposite direction to the pincushion effect applying a barrel effect to the image. [Kuhl et al., 2009] also studied those phenomenons, and they found no significant impact on pincushion distortion. Their experiment includes trials without correction and exaggerated pincushion effect; they found no statistical difference between trials.

The avatar Visualisation of his own body or another person's body improves immersion and the user's capacity to estimate distances correctly. Different studies have explored avatar's effect in representing body in VEs. According to [Greenwald et al., 2017] the simple presence of a basic avatar, such as two static eyes and flat hands, in a cooperation task allow users to feel emotions and transmit expressions easily. [Mohler et al., 2008] states that the presence of an avatar in the VE must help for immersion and distance perception, even if in real life the visualisation of our body does not seem to affect distance perception. However, they notice significant better accuracy when an avatar is modelled in VE. It is worth noting that according to [Leyrer et al., 2011], it is necessary that the participant takes the avatar representation as a representation of himself, and not only as an object of the VE. [Steed et al., 2016] studied the impact of self-avatar on task as letter recollection, mental rotation and hand gesture rate; their main finding was that self-avatar induces better performance for letter recollection, thus according to them, having an avatar does not improve user's ability to perform tasks such as mental rotation, and does not increase the hand gesture mouvement. In summary: the presence of an avatar only brings positive effects.

1.2 Haptic Haptic devices allows users to feel or touche the virtual environment, thanks to receptors stimulation or force feed-back [Wang et al., 2014]. Thank to these devices, VR has proven efficient to train medical students by allowing them to train in a controlled environment [Buckley et al., 2012].

1.3 Auditory Two types of sound can be differentiated: 'localisation', which enriches the virtual environment and stimulates the user to immerse him; it can be anything like wind, bird-song, traffic sound or 'sonification', which is the information displayed through sound (e.g., a voice-over for instruction, information or warning). If those audio feedbacks are correctly set up and linked to visual actions, it will lead to a better immersive experience [Stanney et al., 2003]. [Liu and Kang, 2018] have enlightened an interplay between audio and visual sources that leads to immersion, distress, or happiness. In their study, they compared different streets scale and their sound environment-related. Thereby, they recorded ten 3D videos within different places, there are places as an old town with lower buildings (1-2 floors) and streets tighter (2 lanes), places in the downtown, or more recent city part, thus having higher buildings (skyscrapers) and broader streets, they then asked participants to sit and stay in those different environments, with or without the sound. They deduced some optimal width/height ratios and sound levels for streets.

2 . Interaction

Navigation According to [Bozgeyikli et al., 2019], Point & teleport joystick-like controllers and redirected walking appear to be the best choices for room-scale areas. Point & teleport fits best for applications with long-distance and extensive areas. They are unsuitable in an environment with many obstacles due to the difficulties of aiming at a location behind or partially behind obstacles. Joysticks should be used for fast-paced applications, offer short reaction time, and are quickly taken in hand, but they must be avoided for applications involving obstacles and tight turns. Redirected walking is perfect for a high level of presence in a room-scale application; however, it is hard to make precise movements; thus, it could be harder to manage displacement in an overloaded environment with this method. Compared to redirected walking, walk-in place induces accurate locomotion but less immersion, and it requires more effort for the participants. Hence the application purpose and interactions will guide which movement techniques should be used to enhance the user's experiences. Usually, having proper physical behaviour in VEs is the golden goal, however [Peukert et al., 2019] explained that it could be worth slightly modifying the physics behaviour and elements size to simplify interaction within the VE. Thus, it will generate less or no frustration and a higher level of immersion. Users will be reluctant to reuse the application if difficulties are encountered when using the application or to interact within the VEs. [Stanney et al., 2003] advises focusing on hand tracking as it is the most natural interaction. However, this technique is the hardest to set up in terms of programming and devices (i.e., expensive and less accessible than other standard devices).

Wayfinding There are many possibilities of navigation or orientation; the choice will depend on the type of environment, the purpose of the application and the interactions that will be offered to the user. Users tend to focus on the spatial layout when navigating in a VE and then on their tasks because they want to know where they are and where they must go before interacting with the environment. In this aim, there is need to make evident areas recognisable with their own identity, that way the user will know exactly his location at any moment; it is actually interesting to have an environment easily recognisable and where the user can orient himself easily. For a vast environment, adding visual aids like a compass, map, or colourful path, are all aids to understand a VE layout. [Bozgeyikli et al., 2019]

2.1.2 VE user interface

1 . Engagement

1.1 Immersion [Brown and Cairns, 2004] separate user state in three different parts, "Engagement", "Engrossment" and "Immersion". The possibility to interact with the VEs must be simple, easy to learn, and have a clear and understandable objective. In other words, straightforward interactions should be favoured [Schell, 2008]. Engagement involves first the user's choice to use or not the application. If this first step is accomplished, the users can reach the second state, which involves emotional attachment to the application/game, that part is called "engrossment" [Brown and Cairns, 2004]. Also defended by [Schell, 2008, Reid et al., 2005, Cheng and Cairns, 2005], natural interaction and behaviour are essential when developing VEs, meaning that when the user interacts in a VE, object or VE itself should have a logical behaviour (e.g., object falling down when dropped) In addition, the interaction asked to users should also be in possibility range (e.g., asking the user to lift a car might break the immersion). For the engrossment step, the visual quality shall be appealing; and finally the objective must be engaging, [Baranowski et al., 2008]. If all the previous objectives are achieved, the "immersion" state should be reached, the user is involved in the application and will feel immersed in it.

2 . Side effects

2.1 Visual flow First, the environment wideness does play a role in the user experience; a hallway corridor, for instance, will induce more visual flow than a broad field, thus increasing VR sickness as found by [Lou et al., 2022]. [Cha et al., 2019] studied the effect of a high ceiling on users; they found that a high ceiling induces more positive affective responses, which confirms the previous studies that in a spacious environment, people feels better. However, they state that the height of the ceiling is more influential when in a large room; moreover, an open roof improves interest and visual diversity, which can be stimulating for participants. The literature suggests that smooth navigation with moderate control produces less cybersickness, while rapid head movement may cause cybersickness. No axis of rotation was found to have a greater impact than the others. Implementing an independent visual background (e.g., a grid or a colour line on the ground) may reduce cybersickness. To minimise visual discomfort, [Rebenitsch and Owen, 2016] advised narrowing the horizontal field, limiting the degree of freedom and reducing navigation speed. [Knapp and Loomis, 2004, Messing and Durgin, 2005] used a restricted FOV for distance estimation in real life; they did not find significant underestimation compared to unrestricted FOV in VEs. However, the literature review of [Rebenitsch and Owen, 2016] states that restricted FOV increase cybersickness; indeed, small FOV induce increasing head movement, increasing the visual flux, inducing cybersickness.

2.2 Distance perception Adding visual clues could help for distance perception and size perception, as explored by several studies [Grechkin et al., 2010, Marsh et al., 2014, Kelly et al., 2017], in fact, the human brain uses unconsciously visual clues it can see (e.g., house, window, cars, pen, screen, etc.) to determine size of an unknown element. Whereas in VE, this kind of clue usually does not exist because they are not needed for the application. Thus, it might be interesting to add these elements, which could seem useless for the application purpose but which are useful for application immersion and good representation. [Messing and Durgin, 2005, Renner et al., 2013] highlighted the positive impact and importance of ground texture for accurate distance estimation, such as grid or repetitive pattern. [Kuhl et al., 2009, Messing and Durgin, 2005] have studied the effect of horizon scale or pinched effect on visual perception; the first one found no differences between different pitches, and the second found differences and added additional findings, the perceived distance is compressed but not compressive (i.e. distance compression is not linear). [Kelly et al., 2017] have given a new insight to improve the experience and the belief of the participant in the VE. They proposed to use a virtual environment similar to the physical space where the user is before entering the virtual environment. They had promising results; participants experienced a significantly lower distance underestimation. This solution has a significant limitation; VEs tool aims to bring people to another place where they are in real life. However, this method could be used to transition into VEs, as an extra step before getting users into the virtual place needed. The study of [Ries et al., 2006] found that by modifying the room size, even when keeping the same room, the participants will underestimate distance. Minification and pincushion effect may impact distance estimation according to [Durgin and Li, 2010]. However, the study of [Kuhl et al., 2006] who explored the magnification and minification effect on distance estimation, interestingly found that minification does not have significant impacts, further confirmed by another of their study [Kuhl et al., 2009].

2.3 Cybersickness

Exposure Several studies [Rebenitsch and Owen, 2016, Dużmańska et al., 2018, Schneider and Bengler, 2020] tend to prove that after multiple exposures, cybersickness symptoms will reduce. Their studies found that after multiple trials, the effects among some participants are lower or even disappear completely. Whereas, the severity of symptoms increases during one trial, through multiple trials, the symptom's severity will tend to decreases thanks to adaptation. Some studies have explored the adaptation effects during one day or separate days; they effectively found that participants are more comfortable after multiple trials and face fewer symptoms during their last trial than during their first.

Motion systems [Ng et al., 2020, Lucas et al., 2020] explored the motion system's usage, added to VR tools to stimulate the vestibular system and thus reducing sickness symptoms. According to a previous study, adding a motion system to the VR experience could reduce, induce or even have no effect on cybersickness. It may come from the difference between simulated physical and visual movements. The physical movement must be precisely aligned with the virtual movement to effectively reduce cyber sickness. [Ng et al., 2020] compared different conditions: stationary with only visual motion, synchronised motion-vestibular and a self-referenced environment with active physical movement; as they expected, synchronised performed better than a physical movement which performed better than stationary condition. Looking to the result of [Kemeny et al., 2017] and their literature review, having a fixed reference and a locked head position might reduce cybersickness greatly.

Technology maturness [Geršak et al., 2020] compared three HMD generations, one TV display and a mobile device, to rate the effect of VR matureness on cybersickness; they first expected better resolution, better tracking, and higher image frequency to reduce VR sickness. They show that technology maturness is an important factor, but, surprisingly, older HMD induce lower cybersickness; they propose that this could come from the better graphic quality; apart from SSQ score, there were no significant differences with other recorded data (SC, HR, RR and Skin temperature).

FOV reduction FOV restrictions help participants to stay longer and feel more comfortable in VE. Helping reduce discomfort for the first experiment and thus encourage the second one. In studies using FOV reduction, most participants did not notice the restriction. Even those who saw it specified that they preferred it until it did not reach an undesirable level; different studies support this FOV reduction, such as [Fernandes and Feiner, 2016]. Different ways to achieve FOV reduction are depicted in Figure 2.2[1].

Figure 2.2: From left to right: Basic image / with FOV restriction / blur edges (also done by removing color) / restriction and blur

2.2 CAVE versus HMD

2.2.1 Visualization

Eye-screen distances: The eye-screen distance might impact distance perception. The screens of an HMD are closer to the viewer's eyes than with CAVE ones: thus, the gaze focuses on an image mostly "behind the screen", which can lead to a vergence-accommodation conflict, vergence and accommodation representing both usual distance estimation clues used by our brain to estimate distances in our daily life, especially short distances [Renner et al., 2013]. This well-known conflict has been reported to impact distance perception [Ghinea et al., 2018, Marsh et al., 2014]. In CAVE systems, this distance is usually larger and is not constant during usage as users may physically walk within the CAVE space. Thus, the eyes' accommodation may continuously change as users approach or move away from the CAVE's screens, affecting distance estimation consequently [Marsh et al., 2014]. Additionally, the curvature of the HMD's lenses inside has proven to induce a barrel effect in the image leading to a minification and, thus, to distance misestimation [Kuhl et al., 2006, 2009]. This effect usually does not occur with CAVE systems, as non-curved screens characterize most. A study of

[1]Pictures took by Maël Balland

2018 [Ghinea et al., 2018] tried to find the minimal distances between which a depth distortion using a CAVE or an HMD can be seen. They used the perception adjustment, they found that CAVEs seems more accurate and suitable for short-distance(two-three meters) than HMDs, which therefore would be better suited for long-distance. On the other hand another study [Naceri et al., 2009] found that CAVEs like system (Wide Stereoscopic Screen Display in their study) performed better than HMD for depth perception. [Grechkin et al., 2010] compared large-screen immersive display (LSID), HMD, to real view through HMD; they found no significant differences between LSID and HMD. However, they noticed a significant difference in distance estimation for the real condition view through HMD.

Screen edges: It is worth noting that with CAVEs systems, even if screens and picture display are perfectly well set up, users will be able to notice the screens edges and the tracking system; this could lead to unwanted effects when using CAVEs, such as loss of immersion and presence. For research focusing on distance estimation, this could influence and bias results indeed by seeing edges. Participants may unconsciously or consciously use that as cues for measurement; this issue does not exist with HMDs, making some experiments questionable if they wanted to search about the impact of specific factors such as ground texture or objects colour on distance perception. Moreover, by using a CAVE, the distance to which the object is from the participant could induce three different visual settings [Marsh et al., 2014] as pictured in Figure 1.12.

Environment: In addition to differences in device characteristics, limitations may also arise from the application itself, including the graphics quality, the environment size, the behaviour accuracy, and the interaction easiness. Past study explored the effect of an abrupt change caused when entering a virtual environment. Since the displayed virtual environment is generally different from the real one where virtual immersion is proposed, a sudden change of environment may be too brutal for the brain, which may lead to considering all the visual information displayed when the change occurs as fake [Ries et al., 2006]. Results revealed that immersion and distance estimation could be significantly improved. A study measuring the participants' movements inside a virtual environment, considering both an HMD and a CAVE was conducted [Colley et al., 2015], regarding the results; size, impression, height, movement, control and realism, participants preferred the HMD over the CAVE, even though eight out of thirty participants noticed that the picture was sometimes “choppy” when using the HMD. Additionally, participants reported difficulties in orienting themselves when using the CAVE.

Physical cues: Moreover, CAVEs allow for seeing physical cues, starting with our own body, which can help better estimate distances [Mohler et al., 2008]. For instance, [Marsh et al., 2014] demonstrated that participants tend to use visual cues outside the visual information provided by the environment, such as the screen edges, and use them to estimate distances in the virtual world. In fact, virtual worlds are generally created with only usable or relevant visual cues, thus without any objects considered useless, whereas these may be useful to estimate distances correctly. On the contrary, in the real world, accurate estimations can be performed by looking at surrounding objects. Whatever the VR system, CAVE or HMD, used and their characteristics, distances are usually underestimated in virtual reality compared to reality [Renner et al., 2013].

FOV: The field of view (FOV) changes with the display. The FOV is defined by the extent of what the user can see with his eyes, generally expressed in degrees. The natural human horizontal FOV is around 200°, while in virtual reality the FOV is limited by the screen's size: HMDs usually offer around 100° FOV (recent HMDs can propose a wider FOV though), while CAVE systems offer a much wider FOV [Mallaro et al., 2017]. Past work comparing HMDs and CAVEs has demonstrated that this factor can affect distance estimations [Knapp and Loomis, 2004, Messing and Durgin, 2005, Renner et al., 2013].

FOR: The field of regard (FOR), different from and not related to the field of view, is another noticeable difference between HMDs and CAVEs. The FOR is the visible area that can be assessed when moving our head. The FOR is wider in HMDs than in CAVEs (see Figure 2.3). Indeed, in a typical CAVE system (e.g., a 4-sided 3-meter squared CAVE), if the user faces the front screen standing close to it and he does not move his head but only his eyes, he cannot see the system's borders, and thus, not leave the virtual environment, while with HMDs, if he looks up with his eyes, he will be able to see the edges of the screens. However, in CAVE systems, if a participant looks around (e.g., behind him), he is likely to see outside the virtual world as there may lack a physical screen, while with HMDs, he can look all around without leaving the virtual environment.

2.2.2 Interaction and Navigation

Interaction: As seen in section 1.2, there exist several devices and methods to interact with VEs, either with CAVEs or HMDs. However, studies about interaction metaphors comparison between CAVEs and HMDs are scarce, therefore, to know which hardware to use according to the type of application is not simple, and the choice is thus currently subjective. A study in 2005 directly compared

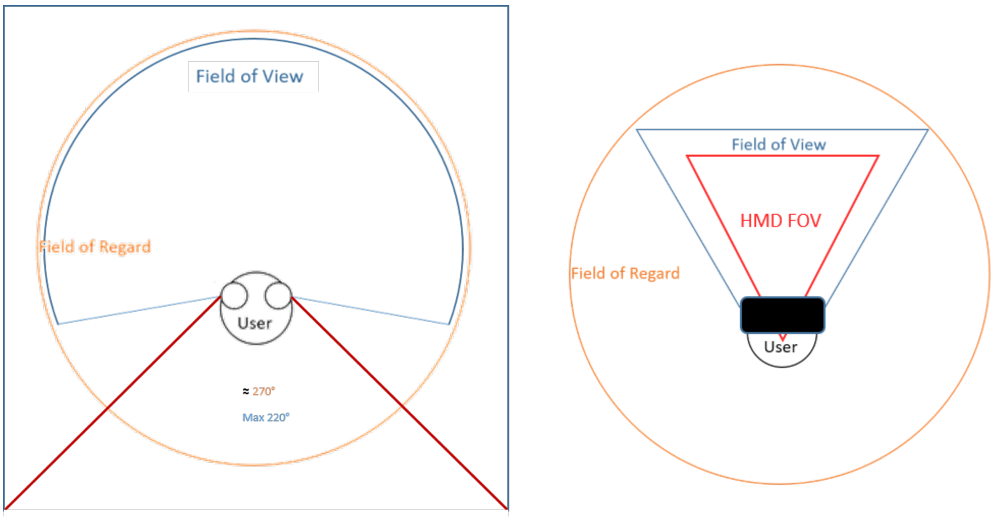


Figure 2.3: Left: FOR limitation with CAVE systems. Right: FOV limitation with HMDs.

three interaction cases, near-space selection, medium space selection and selected and manipulate, with different selection metaphors. They found that between an IPT (Immersive projection technology) and an HMD, performance was better with IPT device. There were also two different tasks, however no matter the virtual device, according to their findings, hands are preferable when selection and manipulation are required. Otherwise, for selection only, the ray-cast metaphor has better results [Steed and Parker, 2005]. [Tcha-Tokey et al., 2017], used an edutainment application named "King Tut VR2", an application about the discovery of an Egyptian tomb. Participants tried the application through a CAVE or an HMD. During the application, they had to follow the journey of Howard Carter and his discovery of King Tutankhamun's tomb through different steps of his day. Participants had to answer a questionnaire about this discovery and what they learned and remembered after the application. They concluded that the user experience was better and interaction more effortless in the CAVE; moreover, the CAVE system has outperformed HMD except for completion time, where CAVE have a higher one. The study of [Colley et al., 2015] compared the different exploration methods experienced by participants through HMD, CAVE and 2D display, using the same controller in each situation. In all three devices, participants moved thanks to an Xbox controller. The authors wanted to see how participants would behave, depending on the device they used. They found that when using 2D display, people tend to take a straight path, while they will have an exploration one when using CAVE or HMD; this result was deduced by path analysis. They also found that the devices impact time completion; the average time to complete the different tasks asked was 3.45 minutes for

2D display, while it was 5.07 minutes for CAVEs and HMDs. Regarding the path participants took and their feedback, they advised not to use CAVEs if precise movements are needed. Moreover, the feeling of height, motion, control, realism and space were better by using HMD than CAVE; their participants noticed that the possibility of moving their head contributes to the feeling of space. A study in 2016 further compared two navigation methods in CAVE systems, gaze directed and pointing directed; their results are clearly in favour of pointing metaphors; indeed it has better results, a better success rate, and a shorter time needed to reach the location moreover, participant feedbacks are in line with these results [Christou et al., 2016].

Navigation: Navigation between each device is distinct; moving around in an HMD or CAVE in a virtual environment has significant differences; users do not have the same sense of presence; in the latter, the user can see his body and, although he can turn his head, he cannot do so in a 360-degree direction because there is no wall behind, which means that, in order to turn around, the user has to use the moving device. In contrast, with an HMD, users can turn around, but as they cannot see their body, even their hands, it can be somewhat disturbing and less immersive in HMD. Navigation differences arise from visualization difference, indeed the metaphor available to move in one device are available on the other.

2.2.3 Presence and Immersion

Looking at past research, embodiment might be essential in allowing the user to immerse in VEs. A known way to increase presence in VEs is modelling the user body; in HMDs, the avatar must be created and synchronised with the user, while in CAVEs, users can see their own body. Thus it might require more development time to make an application for HMD devices. This field is still a hot topic, and even if the avatar impacts user behaviour, immersion and presence, the truthfulness of the avatar is still to be explored. For instance [Gorisse et al., 2018], compared different avatar representations, see Figure 2.4. Moreover, as described by [Hrimech et al., 2011], presence is higher when using an avatar; using an anthropomorphic avatar involves a more heightened sense of co-presence and social presence than a more realistic one. However, from participant feedback, they found that realistic avatars raise participants' expectations, thus, when having a realistic hand, for example, but poor or no animation, it is disappointing for users. A study on acrophobia [Krijn et al., 2004] used and compared CAVE systems and HMD systems, no significant difference has been found in effectiveness, but found a higher presence within the CAVE system. They highlighted that HMD are easier to use for therapists and that for VR tools it does not work with a fair number of patients thus making questionable the validity of these technologies to treat this type of problem.

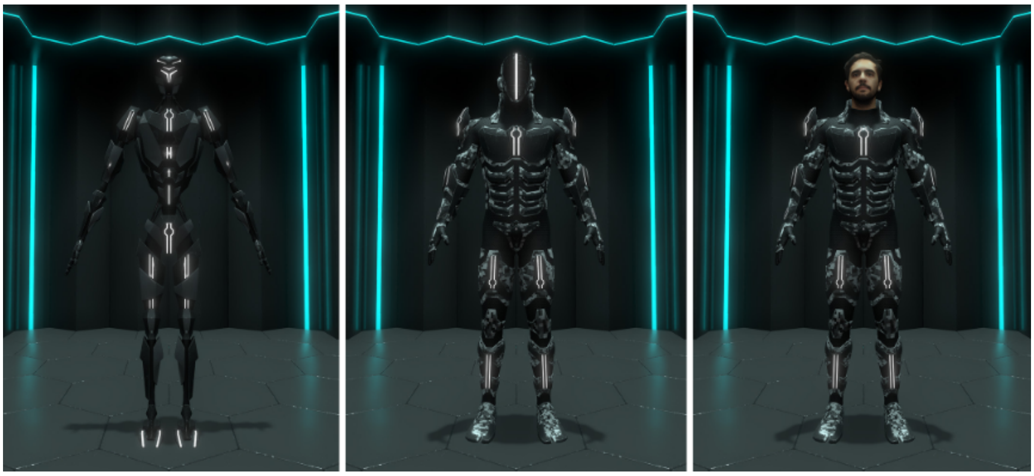


Figure 2.4: Screenshots of the three avatars in the study of [Gorisse et al., 2018], left: Robot / middle: Suit / right: Doppelganger

2.2.4 Usefulness

HMDs and CAVEs do not have really casual or usual utility for the general public [Basset and Noël, 2018]. In the last years HMDs became more popular and accessible, CAVEs meanwhile stayed expensive, hard to set up and unknown to public. In fact, except for specific companies that invest in this kind of equipment and have the time and human resources to work on them, CAVEs systems are not standard. Meanwhile, for small companies, these technologies are often forgotten. Thus, [Basset and Noël, 2018] compared the efficiency of the 2D display and the Mihriad CAVE, which is a desktop-size CAVE, with a more accessible cost; in this way, they wanted to show the utility of a CAVE device for daily engineering design. They compared the efficiency through completion time with different interactions and tasks. Their results are that individuals are more efficient objectively (faster, fewer mistakes) and subjectively (great understanding, lesser workload, preference) doing the specified virtual prototype manipulation task in the CAVE system than in 2D. The study of Kallioniemy et al. in 2017, who primary wanted to find the best hardware for omnidirectional Video (ODV), found that the user experience can exceed expectations, with the result being most significant with HMDs where the user experience surpasses in many factors, enjoyment, clarity and performance [Kallioniemi et al., 2017]. The main difference highlighted by the study arises from the greater difficulty for a user to look around in a CAVEs (a rotating chair), moreover, HMD were considered more immersive than CAVE.

Collaborative environment: CAVEs can be considered state of the art and built for collaborative tasks [Cordeil et al., 2017]. CAVE might be seen as better suitable for collaborative task, as indeed not being cut for external world ease the communication with people outside of the VR. In contrast, HMDs will soon be considered commodity devices, but they are designed for personal experience, in fact even if it is possible to collaborate between different HMD, only one user at time can use a HMD. A study compares both devices for collaborative tasks through three scopes: functionality, collaboration and user experience, they found that collaboration and task achievement were highly accurate with both devices but were substantially faster in the HMD independently of the strategy employed to achieve the task, however, they did not notice differences in communication [Cordeil et al., 2017].

While the creation, preservation and later consumption of information in MR has been considered in existing research, the combination of these actions has seldom been considered [Irlitti et al., 2017]. V-Mail [Imai et al., 1999] and MASSIVE-3 [Greenhalgh et al., 2002] are the most relevant approaches where the capture and replay of rich, multi-modal collaboration. Several application domains might require/use collaboration throught VR tools [Chow et al., 2019], for architectural review [Guerreiro et al., 2014], creative feedback applications [Nguyen et al., 2017, Tsang et al., 2002], training [Yang and Kim, 2002, Chan et al., 2011] and tele-communication [Chen et al., 2015, Orts-Escolano et al., 2016, Regenbrecht et al., 2017]. In their work Chow et al. present a VR environment enabling collaboration in spatial tasks by supporting multi-modal record and replay functionalities and several annotation methods. Other research groups focus on reliving virtual reality experiences and even support the recording and replaying of full body avatars [Wang et al., 2020, Frécon and Nöu, 2019].

Concrete elements: Due to technological advancement and accessibility, there is a difference between the graphics setting of HMDs and CAVEs. Indeed CAVEs are usually supported by powerful and often at the state of the art computers (at least when built), while HMDs are built to fit a consumer market. A CAVE is more expensive, challenging to set up and cumbersome when compared to HMDs, a relatively cheap technology (e.g., around 300€ for cheaper model), moreover, now even smartphones can run VR applications. Hence, it is less common to have at disposal CAVE for research, but they are also less common in industry, thus some studies which initially intend to use CAVE technology turn out to use HMDs for practical reasons. CAVEs are not a suitable solution due to their price and size [Basset and Noël, 2018, Cha et al., 2019], due to the difficulty to move, it usually requires the end-users to come to the physical place where the hardware is. Therefore, spreading this solution to all the industrial sites is unattainable. Having a tracking system is better for immersion than using the familiar keyboard and mouse devices; also, keyboard and mouse are complicated to learn for beginners, while using a tracking system offers more accessible and more natural interaction for users. However, the last one is a less stable technology due to its relative newness, some tracking issues might be encountered, in addition it needs more preparation to make it work. The wearable devices is also a major difference between CAVEs and HMDs; in fact, the former requires the user to wear lightweight wireless glasses, while the latter requires the participant to wear a relatively heavy device on the head, which is sometimes also connected to the computer via a cable, limiting movement and freedom of motion. Concerning interaction, both devices use wireless controllers to interact in the VE, but in one system user see controllers while in the other controller need to be rendered through the VE.

As VR technologies rapidly progress, distance estimation with recent HMDs seems to improve [Kelly et al., 2017], which may originate from an enhancement in image quality, FOV, miniaturization, focus depth or tracking system. These technical issues may disappear with technological progress [Kelly et al., 2017, Renner et al., 2013, Cordeil et al., 2017], thus improving all aspects of user experience, including cybersickness, distance perception or eye strain. These improvements are however less observed with CAVE systems, as they tend to become prevalent in research labs or big companies, and their price are still high, making them not easily available for personal use or almost impossible.

2.3 Scientific issues

This section presents the scientific issues related to the differences between our two devices.

2.3.1 Cybersickness

Cybersickness may be significantly impacted by the type of displays considered for virtual immersion. Many researchers have studied the issue of VR cybersickness, about its effects, and the strategies to measure its occurrence and find the symptom causes [Dużmańska et al., 2018, Kim et al., 2018, Malińska et al., 2015, Rebenitsch and Owen, 2016]. Though, comparative studies between CAVEs and HMDs are however still rare, mainly because of technical and availability issues, and may sometimes contradict each other. Past research has reported differences between CAVEs and HMDs, with a lower occurrence of cybersickness in CAVEs than with HMDs [Kemeny et al., 2020, Polcar and Horejsi, 2015]. Reasons may lie in the ability given by the CAVE to keep viewing our own body and external references, which may impact the severity of cybersickness, as measured by objective indicators, such as heart rate, skin conductance and postural stability [Chardonnet et al., 2017, Galeazzi et al., 2006, Stoffregen et al., 2000]. Nonetheless, some studies also reported no significant differences between both VR systems [Colombet et al., 2016, Kemeny et al., 2017], though it seems that participants often prefer CAVEs to HMDs [Kwok et al., 2018].

2.3.2 User behavior

[Mallaro et al., 2017] used the IFSTTAR CAVE (see Figure 1.10) and HMD to analyse pedestrian behaviors, and they drew the following conclusion: participants in the HMD condition were less conservative and less discriminating in their gap choices and timed their entry into the roadway more tightly than those in the CAVE condition, moreover in the HMD condition user had somewhat more time to spare when exiting the roadway, despite choosing smaller gaps and standing further from the roadway at the start. The restricted FOV could lead to this kind of decision; in the HMD, users might have been less aware of their surroundings. [Bowman et al., 2002] asked users to go through corridors, forcing them to use virtual rotation to turn, using either CAVE or HMD systems; following their results, they advise using HMDs rather than CAVEs for VEs that require rotation.

[Grechkin et al., 2014] compared navigation techniques; they were interested in user behaviour based on the devices and locomotion metaphors for an on boarding task. Displays were a large-screen projection display setup with three side walls and a head-mounted display; the modes of locomotion were physical walking or a joystick that controlled locomotion. Users had to choose the timing to board a train that passed but did not stop. The display type does not affect participant choices to board or not. While the locomotion method did, they declare that the walking condition was "more slowly" which could have impacted users' choices and thus, their results, and that independently of the actual metaphor.

A study in 2019 compared HMDs and SWDs for egocentric distance and user experiences, in term of time completion, comfort, accuracy and cybersickness. According to their results, the accuracy is better with stereoscopic widescreens display, but there is no significant difference for time completion or cybersickness [Lin et al., 2019].

Another study compared the size and distance of stimuli under minimal, moderate, or maximum visual cues in an alien environment [Park et al., 2021], applicable for space training conquers, building a base in a vast empty environment or pilot training. Their study might apply to polar and submarine exploration, such as deserts or the deep sea. Their result indicates an underestimation in minimal and maximum environmental visual cues and a tendency to overestimate in the moderate one. Participants overestimated 65cm and 100cm while underestimating 150 in the SWD, but they underestimated all distances in the HMD condition. Depth perception is substantially better in a minimal environment, while height perception is better in a maximum cue environment. More generally, their results suggest that familiar visual cues facilitated better size and distance estimation than unfamiliar cues, exotics cues might disturb perception.

2.3.3 Synthesis

Table 2.1 sums up the differences between HMD and CAVE that have been highlighted in the previous sections.

Table 2.1: Differences between HMDs and CAVE systems

	CAVE	**HMD**	**Impact**
Weight / Size	>1 00000 g Room scale : >3 square meters	500g - 1 100g Hold in a box	CAVE systems are harder to move. It takes a room dedicated to this device. Meanwhile HMD are handheld device
Price	>10 000	300€ - 4 000€	CAVEs are not available to the public and they require investment. While HMDs are accessible
Weight device worn	≈ 100g	500g - 1 100g	-
Resolution	Variable Up to 4 000 px	Quest 2 : 3 664 x 3 840 px Vive Pro : 4 896 x 2 648 px Varjo : 5 760 x 5 440 px	Visual quality. Users can see the pixel, valid for both devices
Edge / Helmet contour	Visible	Visible	If noticed, this factor might impact user experience
Eye-Screen distance	Variable : 0 to 3 meters	Variable : ≈ 1m	-
Field of view	Complete 200° - 220°	Quest 2 : 104° Vive Pro : 116° Varjo : 115°	With an HMD, users can see the boundaries of the screen, it is less likely to happen with CAVEs
Field of regard	Theoretically up to 360° Commonly lower (210°)	360°	-
Body visualization	Yes	No	It helps to reduce cybersickness to see an avatar in VE. The impact in CAVEs is yet undefined.
Contact with real world	Yes	View cut off	It can be limiting in collaborative tasks.
Lighting	Low	High	HMD screens produce light, while CAVEs screens receive light, which makes the lights look duller with the last one.
DOF	6	6	Allow users every kind of movement.
Interaction	Everything	Everything	Any devices is usable with both devices.

2.3.4 Research questions

The title of this thesis is: "User experience in virtual immersion: a study of scale factors for a similar perception in a CAVE and an HMD". Following the previous state of the art, and the differences we have highlighted. We decided to focus on the differences that we believe are crucial in differentiating the two systems. Thus, the differences that affect the user experience and that are not likely to be improved in the coming years have been the subject of experimentation. we first examined the evolution of VR devices and presented the characteristics of today's most popular ones. Subsequently, we sought to characterize the user experience and the different characteristics of the devices that could influence it. We deeply explored two particular devices: CAVE systems and VR headsets. We found that various research areas use one or the other without giving any particular reason, advantage or preference. Given this lack of objective comparison, we asked ourselves whether a CAVE and a Head-Mounted Display offer different user experiences. This led us to define two more precise research questions:

- **Which are the device's characteristics that might affect users' experience while executing a particular task (e.g., navigation or manipulation)?**
- **Is it possible to have a similar user experience with these two technologies?**

To answer these broad research questions, we selected more specific points, allowing us to compare the two devices while limiting the biases that could arise from other factors as much as possible. In this sense, for our experimental studies, we have chosen to focus on some of the above-mentioned dissimilarities. We chose them because they are inherent differences in the technologies, which will not be resolved by technological developments in the coming years. We have also selected specific factors that could influence the user experience according to our literature review.

Therefore, we made the following working hypotheses:

- **The weight of the device worn, helmet for HMD or glasses for CAVE, would impact the perceived distance walked.**
- **The eye-screen distance, different between HMD and CAVE, would have different outcomes on the distance estimation during short-range interaction.**

- **The FOR being wider in HMD would favor this display for navigation tasks by reducing the time to complete the task, the need to perform head rotations, and by increasing positive feedback from users.**
- **The visualization of the body in CAVEs would not overcome the higher optic flow compared to HMDs, which would lead to a higher cybersickness level in the former (i.e., CAVE systems).**

2.3.5 Key factors

The difference in the hardware worn by users will always be existing between CAVEs and HMDs (i.e., glasses versus helmets). Indeed, unless there is a surprising development, immersive reality headsets will not weigh less than one hundred grams, and as previously stated, worn weight might influence perceived distance. Second, the eye-screen distance is different between both our systems. For CAVEs, this distance is not fixed, while it is for HMD. In fact, this distance might have an effect on perception, impacting distance estimation. The FOV and FOR depend on the device. All HMDs offer a 360° FOR, while CAVEs do not usually provide a complete FOR (six-face CAVEs are scarce). Both devices provide a limited FOV (human field of view is around 210°). These limitations and differences might impact users' behaviors for specifics task, especially when it requires looking around. Finally, all the previous factors might impact cybersickness. Therefore, it is important to conduct experiments to highlight how devices' differences might impact the cybersickness experienced by participants.

Chapter 3

Experimental Approach and Experiments

This chapter presents the different experiments carried out, through a brief introduction, the protocol and the results. The first two experiments presented focus on physical differences, which are the weight of the apparatuses and the limitation of FOR. The next two experiments concern differences related to the user perception, thus, the ego-centric perception and simulator sickness.

3.1 Device Characteristics

First of all, different VR devices were used during this work, a description of each device is given here.

3.1.1 BlueLemon

The BlueLemon is composed of five screens (front, left side, right side, top and bottom). The dimensions of the BlueLemon are 3.40 m (W)$\times$2.70 m (H)$\times$3 m (D) (see Figure 3.1). On each screen, active stereoscopic retro-projection is performed through Mirage 4k25 projectors, achieving a resolution of 4096$\times$2160 pixels at a 120 Hz framerate. An ART tracking system[1] with eight infrared cameras placed on the corners of the CAVE is installed to track users and interaction devices. Six computers control the system via MPI. Virtual environments are created under Unity3D, and the whole display and interaction process is managed by a library called iiVR and written in C++, developed internally to connect all devices within the BlueLemon, including interaction devices. Here, an ART Flystick device was used to interact (navigate and manipulate) within virtual environments.

[1]https://ar-tracking.com

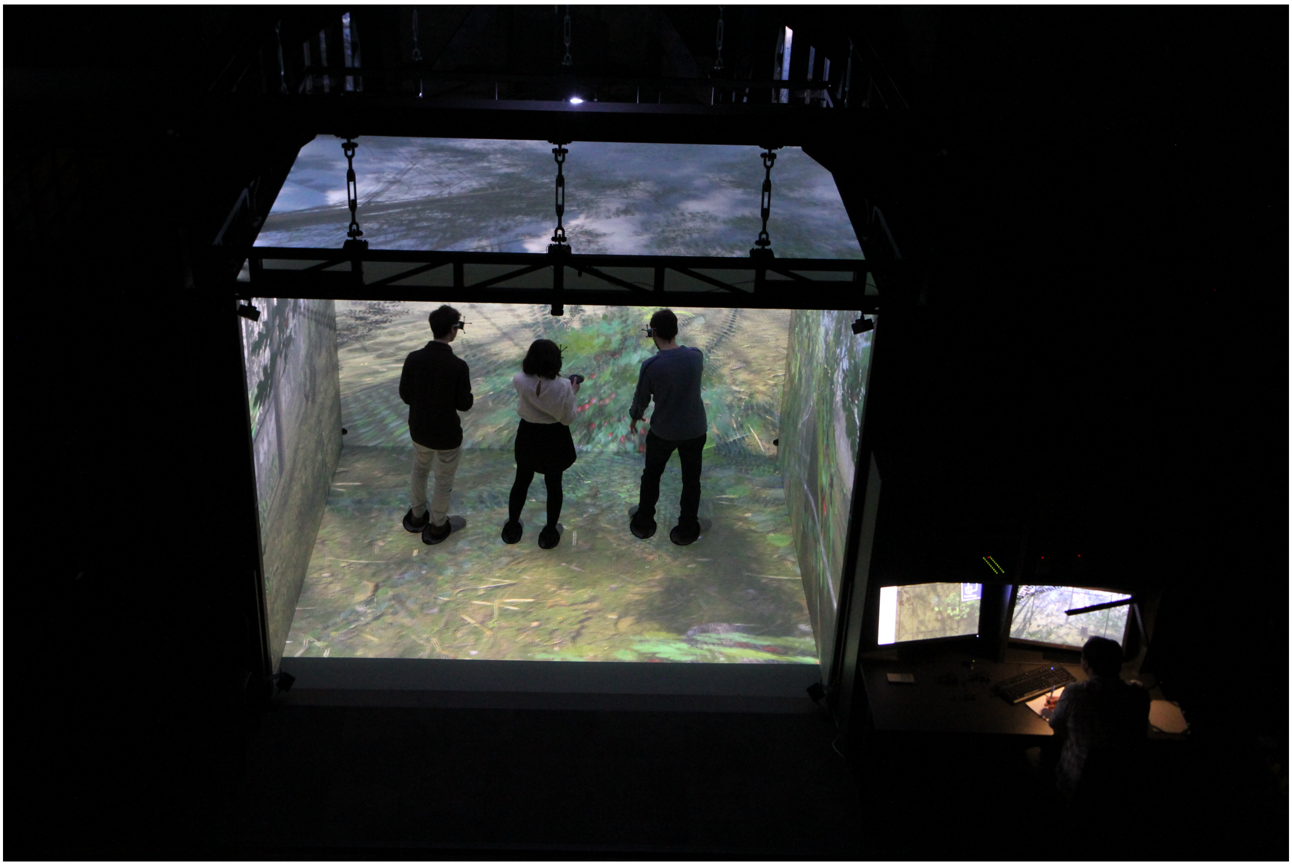


Figure 3.1: BlueLemon

3.1.2 Immersive CAVE room at the CRVM in Marseille

This CAVE is composed of three vertical screens and a floor, vertical screens are 4 meters high and the floor surface is 3x3 meters, also equipped with stereoscopic projection and a motion capture system. Thus it has no ceiling/top screen. Despite the absence of a top screen, the height of the side screens allows to have a full field of vision, and not to see outside the virtual environment (see Figure 3.2).

3.1.3 Head-mounted display

An Oculus Quest2 and an HTC Vive Pro were used, see Figure 3.3. The HTC Vive Pro is a well-known HMD providing with a resolution of 1440×1600 pixels (2880×1600 for both eyes) at a 90 Hz framerate, and a 110-degree field of view. The inter-pupillary distance (IPD) can be adjusted to each user thanks to a control knob on the HMD. The Oculus Quest 2 is the HMD from Meta, out since 2020,

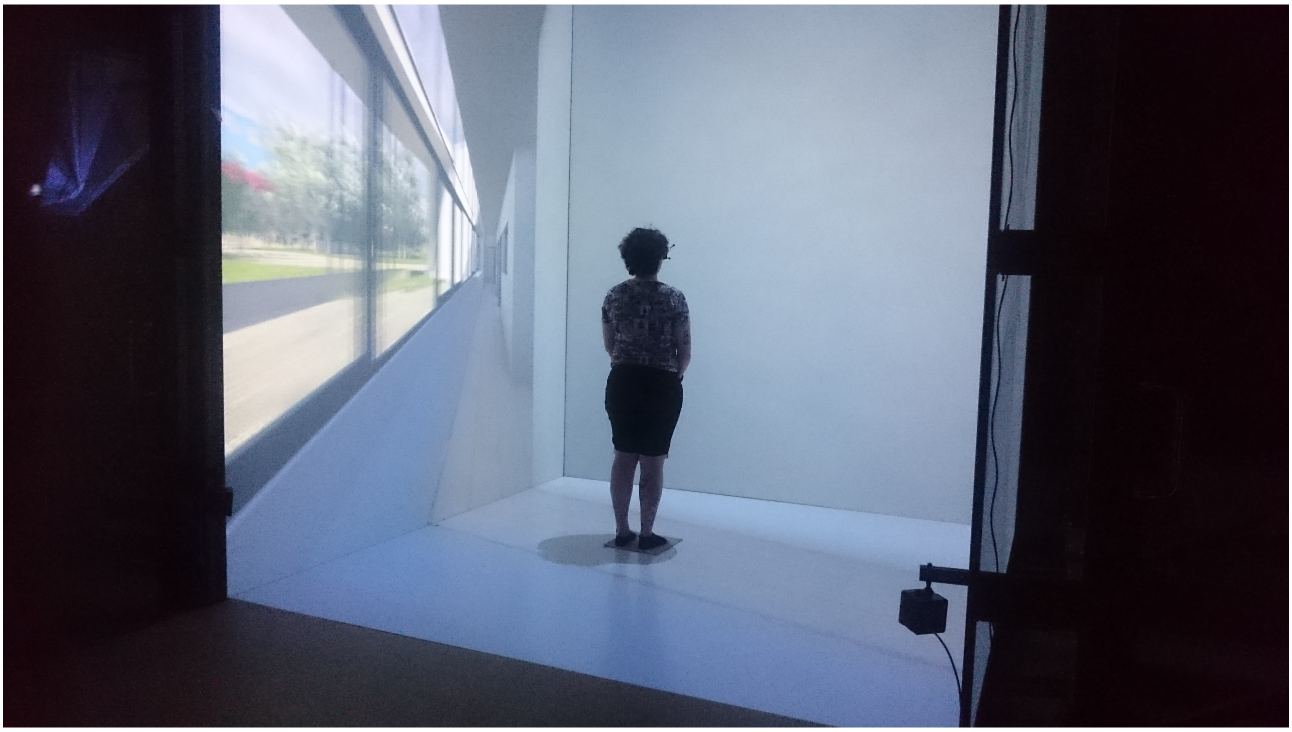


Figure 3.2: CRVM's CAVE

it offers a resolution of 1832×1920 pixels (2880×1600 for both eyes) at a 90 Hz framerate, and a 89-degree field of view. The IPD can be adjusted by moving the lenses inside the HMD, following notches, thus offering less precision than the HTC. The two devices come with controllers, see Figure 3.4.

The specification are detailed in the tab subsection 1.1.3

Table 3.1: HTC vive Pro and Quest 2 specification

	HTC Vive Pro	**Oculus Quest 2**
Screen	Dual AMOLED 3.5" diagonal	LCD Fast Switch
Resolution	1440 x 1600 pixels per eye	1832 x 1920 pixels per eyes
Refresh rate	90 Hz	90 Hz
Field of view	110 degrees	97 degrees
Weight	1038 g	503 g

Figure 3.3: Left: HTC Vive Pro. Right: Oculus Quest 2

Figure 3.4: Left: Flystick for CAVEs. Middle: Oculus Quest 2 controller. Right: HTC Vive controller.

3.2 Impact of device weight on distance travel estimation

3.2.1 Introduction

The HMD's weight is a critical differentiating feature *vis-a-vis* CAVEs. While HMDs usually weigh between 500 g and 1000 g (1038 g for the HTC Vive Pro, 503 g for the Oculus Quest 2, 600g for the PlayStation VR), the device worn by users in CAVE systems (typically, tracked stereoscopic glasses) are lighter, usually less than 100 g. The HMD's weight is five to ten times larger on the users' heads than with CAVE systems; we could rightfully wonder whether this factor impacts the distance perceived when walking with such devices on the head. The HMD's weight might influence distance perception when the application requires physical movement. Past research has indicated that the intention to interact within a virtual environment, the expected effort, or the weight inflicted on users impact distance perception [Proffitt et al., 2003, Renner et al., 2013, Witt et al., 2004]. Whereas, [Nilsson et al., 2015] who investigated HMD weight with two locomotion methods, treadmill and walk-in-place, comparing two different weights; did not draw any significant difference caused by device weight.

This experiment concentrates on the HMD's weight itself, as past research has assessed its contribution but keeping biases, such as virtual reality visualization or a restricted FOV. Here, by removing every possible bias to better characterize the effect of weight on perception, so the vision was removed during trials, only the weight of the helmet is the factor that changes between the two modalities.

3.2.2 Research questions and hypotheses

- When using a CAVE, we wear only a pair of light glasses, while when using an HMD, we wear a helmet with a possibly significant weight. Therefore, does the device's weight significantly affect perception and to which extent?

This question addresses directly to the second research question of this thesis : *Is it possible to have a similar user experience with these two technologies?*, indeed, we want to know if the helmets weight will influence the user experience in the context of a physical displacement, comparing to relative light CAVE glasses. As this factor is difficult to adjust/modify, finding a significant difference in this study would answer our question negatively (for tasks that require physical movement), as it would be difficult to have a similar user experience.

An experiment designed to isolate the HMD weight factor from other factors that could impact the user's distance perception has been performed to answer this first question. The Oculus Quest 2 HMD was worn by participants and a blindfold in another trial, ensuring that participants could not see the real environment surrounding them in any way. Unlike previous studies, which use perceived targets or perceptual matching, in this study participants could not estimate the distance between two entities or between them and a previously seen target, but, they had to evaluate their own walking distance. The following hypothesis was made:

H1. The HMD's weight will negatively impact the distance participants travelled, i.e., they will overestimate their walking distance when wearing the HMD and the blindfold.

In other words, is the weight of the HMD a crucial factor to consider when developing a VR application ?

3.2.3 Experiment design

Participants

21 participants (mean age= 25 ± 15, 5 females) were recruited from different backgrounds inside and outside the university. They were all requested to be free for at least one hour to participate. Upon arrival, they were asked to sign a consent form and fill in a short demographic form. Before and until the end of the whole experimentation, the purpose of the experiment was hidden from the participants. At the end of the experimentation, they were free to ask any question they could have.

Protocol

Participants were guided to the experimentation room. They could see that they had space and would not have to worry about hitting something during the experiment. That was important to mention it since they would be blindfolded. Thus, they should not restrain their steps due to the uncertainty of the real environment. We also ensured them that the experimenter would stay beside them during the whole walking; thus, if they lost stability, he would be there to secure them. In this room, a rope was installed as a tutor to ensure participants walked in a straight line (see Figure 3.5). The rope was stretched to remove any clue of distance that could be perceived by the rope bending. Moreover, there were asked not to squeeze or sustain on the rope but to hold it slightly throughout the travels. Participants were asked to walk for 2, 3 and 5 meters while wearing either a blindfold only (modality “B”) or both a blindfold and the HMD (modality “H”). We asked participants not to count their steps and to walk in a usual way. In the latter condition, the HMD was set to the participants when they arrived at the starting point of the rope. Throughout the experiment, the HMD was turned off to avoid any bias related to image visualization. They were requested to walk along the rope 18 times under one modality (either B or H) and 18 times under the other. The order of walking distances and modalities was counterbalanced. After each trial, the travelled distance was recorded. After completing all trials, which took approximately twenty minutes, participants were taken back to the first room to rest.

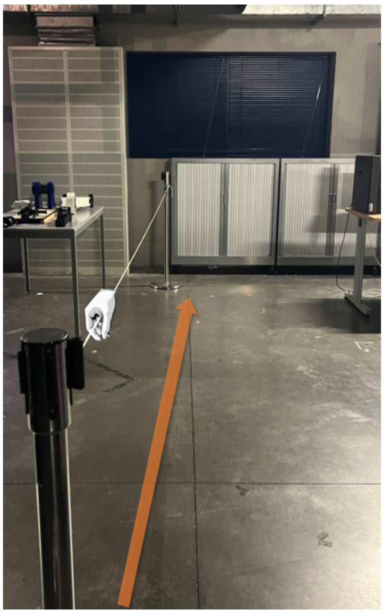


Figure 3.5: Room for the experiment. Participants were asked to hold the rope slightly as depicted by the virtual hand.

3.2.4 Results: Impact of weight on distance travel estimation

For all the data collected, we performed normality checks. When data were found normal, ANOVA tests were used, and t-tests were run for post-hoc analyses when applicable. On the contrary, when data were found not normal, we conducted Kruskal-Wallis tests with Mann-Whitney tests for post-hoc analyses when appropriate. The significance threshold was set to .05.

The experiment led to a 2 (conditions)×3 (distances) repeated measures design. An ANOVA test on distances revealed significant differences between distances, $F(2, 123) = 3.432, p = .035$. Post-hoc pairwise t-tests showed no significant difference between two and three meters ($t_{2m,3m}(82) = 1.140, p = .257$), and between three and five meter ($t_{2m,5m}(82) = 1.538, p = .128$), while a significant difference was observed between two and five meters ($t_{2m,5m}(82) = 2.576, p = .012$). The means and standard deviations are displayed in Table 3.2.

Table 3.2: Distance asked, error means to target distance and standard deviations

Modality	*2mB*	*3mB*	*5mB*	2mH	3mH	5mH
Mean (%)	4,523	-0,5	-6,425	0,492	-3,746	-8,473
Standard Error	3,506	2,682	2,333	2,070	2,101	1,940

A t-test to compare distance modality impact on distance walked revealed no significant effect between modalities, $t(124) = 0.985, p = .326$. We then compared each modality distance by distance, however, no dissimilarities were found, $t_{2B-2H}(21) = .645, p = .523, t_{3B-3H}(21) = .626, p = .534, t_{5B-5H}(21) = .232, p = .663$. Last, one-sample t-tests to compare the percentage error between the aimed distance and the theoretical one (see Figure 3.6). No significant differences were found for two and three meters independently of the sytem, $t_{2m,B}(21) = .858, p = .401, t_{3m,B}(21) = -0.113, p = .911, t_{2m,H}(21) = .146, p = .885, t_{3m,H}(21) = -1.162, p = .259$, whereas for five meters, we observed a significant difference for modality H, $t_{5m,B}(21) = -1.744, p = .097, t_{5m,H}(21) = -2.975, p = .0.007$.

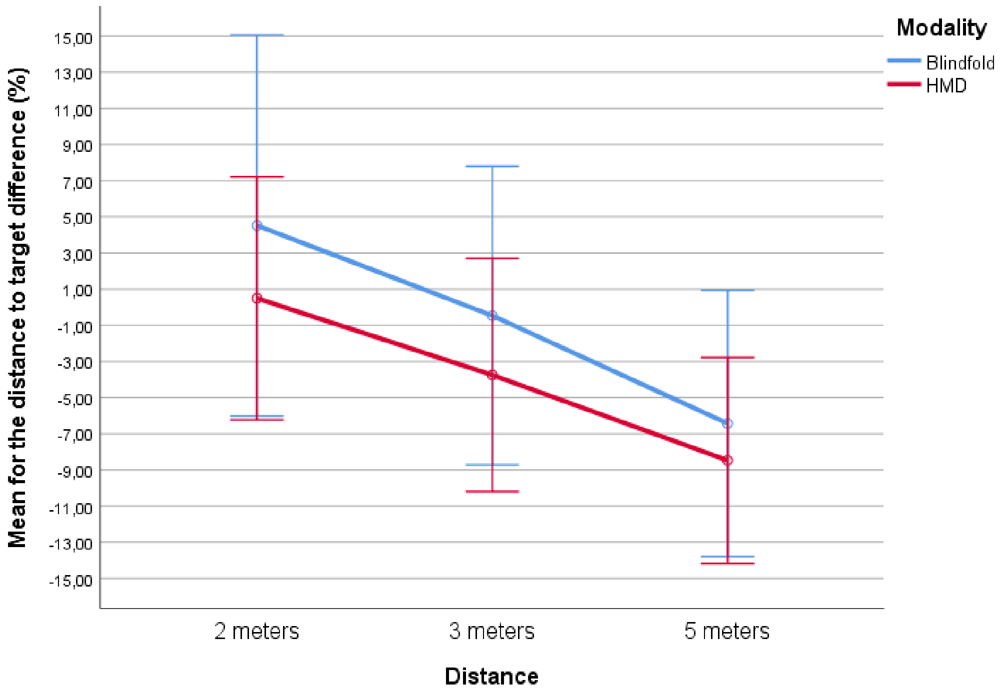


Figure 3.6: Mean for the distance to target differences (%) for each distance by modality

3.2.5 Discussion

Travel distances were significantly overestimated for distances over three meters, no matter with the HMD worn or not; however, it is noticeable that, with the blindfold worn, distances were slightly more overestimated than with the HMD. According to the study, the HMD's weight itself can impact travel distances above three meters, partly assessing the first hypothesis H1, but also confirming past work that distance underestimation can originate from the HMD's weight [Grechkin et al., 2010, Willemsen et al., 2004, Vienne et al., 2020, Nilsson et al., 2015]. Additionally, some participants reported being destabilized by the HMD's weight, leading them to walk less far. Several reasons can be proposed for this observation. First, the HMD's weight may induce the body's centre of gravity to move out of the participant's postural stability area. Second, since the participants' vision was occluded from reality, it may have impacted postural stability [Galeazzi et al., 2006].

As a consequence of these results, the HMD's weight, not present with a CAVE, can be ignored if the setup does not involve a real displacement further than three meters.

3.3 Device impact in a navigation application

3.3.1 Introduction

As seen earlier (subsection 2.2.1), the FOV and FOR of CAVE and HMD are noticeably different. Indeed, these differences may lead users to adopt other behaviors for exploratory tasks, such as a greater need to virtually rotate the view in order to look around, perhaps leading some users to take different paths to avoid this rotation which can be unpleasant. Cybersickness in CAVE has not been widely covered. [Sharples et al., 2008] explored the difference between displays for virtual reality-induced symptoms and effects. Their study used HMD, desktop, standard projection and reality theatre (horizontally curved screen), with two different modalities, passive and active movement. Their results highlight that HMD and reality theatre induce more Virtual reality induced symptoms and effects. Another study compared CAVE-like system (IRIS Renault, see Figure 1.10) and HMDs in a driving simulation use case. They did not find differences between the two devices, but rotational motion induces more cybersickness effects than longitudinal motions [Kemeny et al., 2017].

For interactive tasks, some comparative studies have revealed that participants were significantly faster to perform tasks when using HMDs [Cordeil et al., 2017], however it was for a specific collaborative task. Furthermore, users tend to make choices faster with HMDs, when they are asked to cross a road or to board in a train [Steed and Parker, 2005, Grechkin et al., 2014], while they are faster to perform selection tasks only with CAVE-like systems, though better results can be achieved when using HMDs for selection and interaction.

3.3.2 Research questions and hypotheses

- Difference in FOR and FOV: if the same theoretical virtual environment is offered with both systems, will the divergences in FOR and FOV significantly impact user perception and the way users navigate in a virtual environment?

This question relates to the first research question: *What are the device's characteristics that affect users' experience while executing a particular task ?*, we want to know if the FOV or FOR, which is different between our two devices, will impact the user experience. These results could eventually lead to a similar user experience on both devices, and perhaps the ability to use either system while expecting similar results. A positive response would lead us to recommend FOV or FOR modifications in the development of VR applications to achieve a similar user experience (e.g., reduce the FOV in CAVEs, or ask users not to rotate their bodies when using HMDs).

This experiment aims at comparing navigation in wide virtual environments using both a CAVE and an HMD, requiring users to rotate substantially. The goal is to compare the differences induced by the FOR in such application, in terms of cybersickness level and navigation movement. The metric used is the level of cybersickness. The devices used were the Blue Lemon and the HTC Vive. Participants are immersed in a two-floor indoor environment consisting of 25 rooms per floor and corridors, each room being identified by a different sign (see Figure 3.7), and they are asked to complete a navigation path passing through different rooms. A virtual elevator was included to go from one floor to another. The design of the environment is complex on purpose, to force participants to involve themselves in the navigation task and spend time to complete the task. To help participants orient themselves inside the virtual environment, a map was provided to them with different signs corresponding to the rooms (see Figure 3.7 right). We made the following hypotheses for this experiment:

- **H1**. Due to the restricted FOR in the CAVE, the completion time will be higher in the CAVE than with the HMD.

- **H2**. Participants will prefer the HMD because of an unrestricted FOR and better immersion.

- **H3**. Cybersickness will be lower in the CAVE, thanks to the ability to still see his/her body.

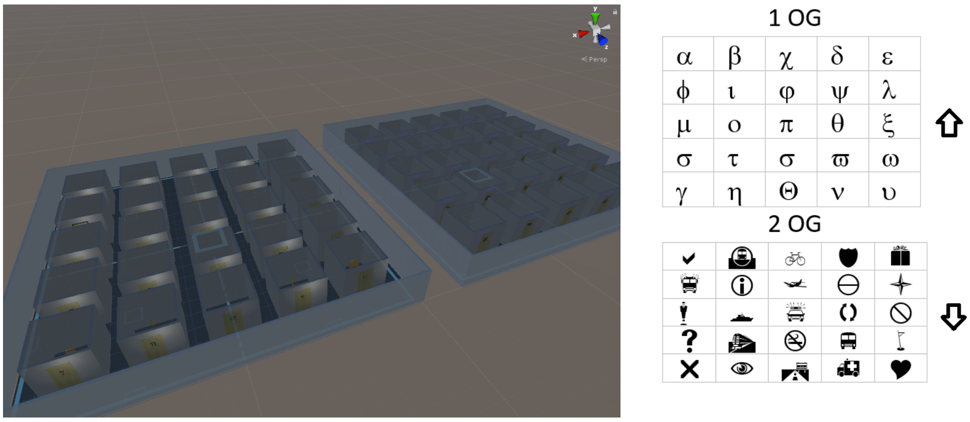


Figure 3.7: Left: Virtual environment for the experiment. Right: Map to help participants orient during the experiment.

3.3.3 Experiment design

Participants

21 participants (mean age= 25 ± 15, 5 females) were recruited from different backgrounds inside and outside the university. They were all requested to be free for at least one hour to participate in this experiment. Upon arrival, they were asked to sign a consent form and to fill in a short demographic form. Before and until the end of the whole experimentation, the purpose of the experiment was hidden to them. At the end of the experimentation, they were however free to ask any question they could have.

Protocol

The application was presented to the participants (Figure 3.7), the tasks to complete and how to interact in the virtual environment. The application demanded to navigate in the virtual environment, to interact with virtual doors and an elevator. In each modality (C and V), a few minutes were given to the participants to get familiarized with the environment and the interaction metaphor. During this phase, the experimenter helped participants reach the first virtual room, asked them to attain a specific point in the virtual environment, and ensured they understood how the provided map works. Participants were free to ask questions concerning the application during this training session. After this familiarization phase, they start the experiment. They were required to visit ten virtual rooms to finish the experimentation. Two navigation paths were built, one for the first trial and one for the second, either in one device or the other, by symmetry to have the same theoretical length (which has been verified further with data analysis). Once a room was reached, participants had to open the corresponding door through which they could see a sign indicating to which room they had to go, thus leading them to a new location. Modalities order was counterbalanced. For each modality, recorded parameters were the completion time, the head rotation, and position in the virtual world. Additionally, physiological data were collected thanks to an Empatica E4 wristband. This wristband allowed the collection of the skin conductance (measured by the electrodermal activity–EDA), the heart rate and the skin temperature at a 4 Hz frequency and precision around the μS for the EDA. These parameters are known to be related to the cybersickness severity [Dużmańska et al., 2018, Malińska et al., 2015, Plouzeau et al., 2018]. Furthermore, after each modality (C and V), participants had to fill in the Virtual Reality Sickness Questionnaire and the Misery Scale questionnaire. These questionnaires were chosen rather than the well-known Simulator Sickness Questionnaire (SSQ), despite its intensive use in VR studies, to cope with remarks raised by several researchers on its relevance to VR [Kim et al., 2018, Kemeny et al., 2020].

At the very end of the experiment, participants were asked to provide feedback about the whole experimentation process, and they were invited to ask any questions about the study or the application. Moreover, we inquired them to specify which device they would choose to do this experiment once again and the reasons for their choice.

3.3.4 Results: Device impact in a navigation application

For all the data collected, we performed normality checks. When data were found normal, ANOVA tests were used, and t-tests were run for post-hoc analyses when applicable. On the contrary, when data were found not normal, we conducted Kruskal-Wallis tests with Mann-Whitney tests for post-hoc analyses when applicable. The significance threshold was set to .05.

Physiological data

Physiological data (heart rate/skin conductance) and psychological data (MISC and VRSQ) were collected to assess cybersickness, as well as behavioral data to compare users' behaviors related to the use of different VR systems during the experiment. The data of four participants were removed from the analysis of the results, two stopped the experiment due to cybersickness, one had to leave before the end for personal reason and one of them because of data recording issues. Heart rate (HR) and skin conductance (SC) during the experiment were recorded, thanks to the E4 wristband. SC has been removed from data analysis because a notable change has been observed during the experimentation; however, two external factors could have impacted this data. The experiment was carried out in two different rooms with uncontrolled temperatures, in addition, the CAVE emits a significant amount of heat, which heats up the room during the day. As a consequence, some participants noticed a noticeable heat change between each room, and some complained about the hotness in the CAVE, especially at the end of the day when the device was turned on for several hours. The SC data were then considered not exploitable.

Concerning the heart rate, a normalization was first applied to the participant's heart rate to compare their evolution by removing differences between individuals. A Mann-Whitney test revealed that the heart-rate was significantly higher with the HMD ($M = .594, SD = .041$) than with the CAVE ($M = .529, SD = .037$), $U = 144, p = .05$. A Wilcoxon signed-rank test for paired samples between trials for each participant was run, showing no significant differences for four participants. Among participants, seven had a higher HR with the HMD and six with the CAVE and based on Kendall's correlation test, these differences were not induced by the first trial modality, $r = -.225, p = .435$. No statistical difference between heart rates was found.

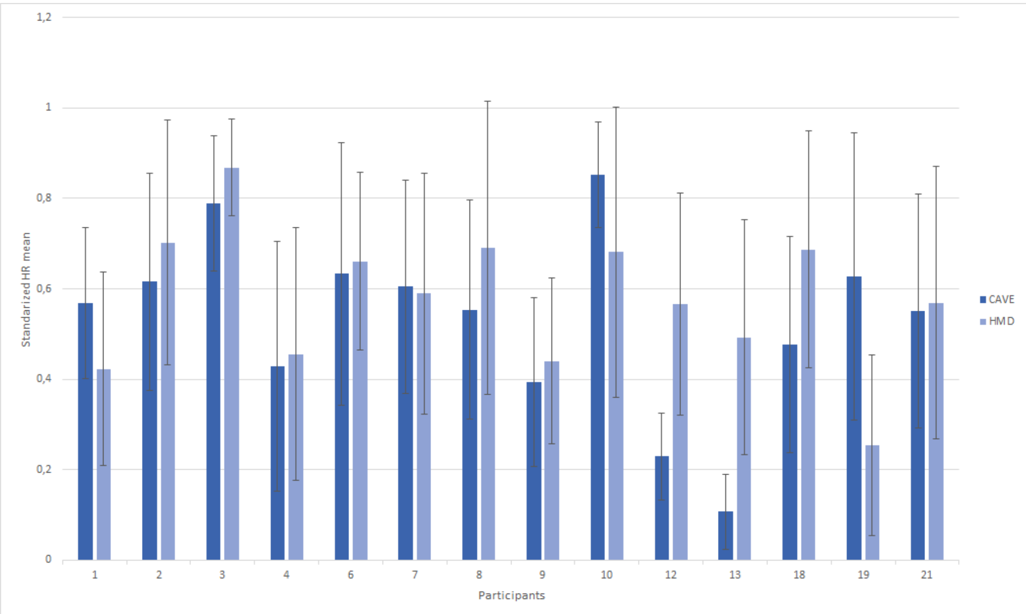


Figure 3.8: Standardized mean of the participants' heart rate

Psychological data

Besides physiological data, participants had to filled VRSQ and a MISC after each trial. The VRSQ contains nine items, while the MISC consists of a single ten-point Likert-scale question. A Mann-Whitney test between modalities on VRSQ and MISC results did not show any significant differences between both hardware, $U_{VRSQ} = 106.5, p = .211, U_{MISC} = 112.5, p = .137$. A finer analysis of each VRSQ item also failed to show differences (see Table 3.3). Though, it may be noticed that, except for the "blurred vision" item, the scores for all the items were higher for the CAVE modality, see Figure 3.9. A similar observation could be done with the MISC's scores ($M_{CAVE} = 1.47, M_{HMD} = 1.06$).

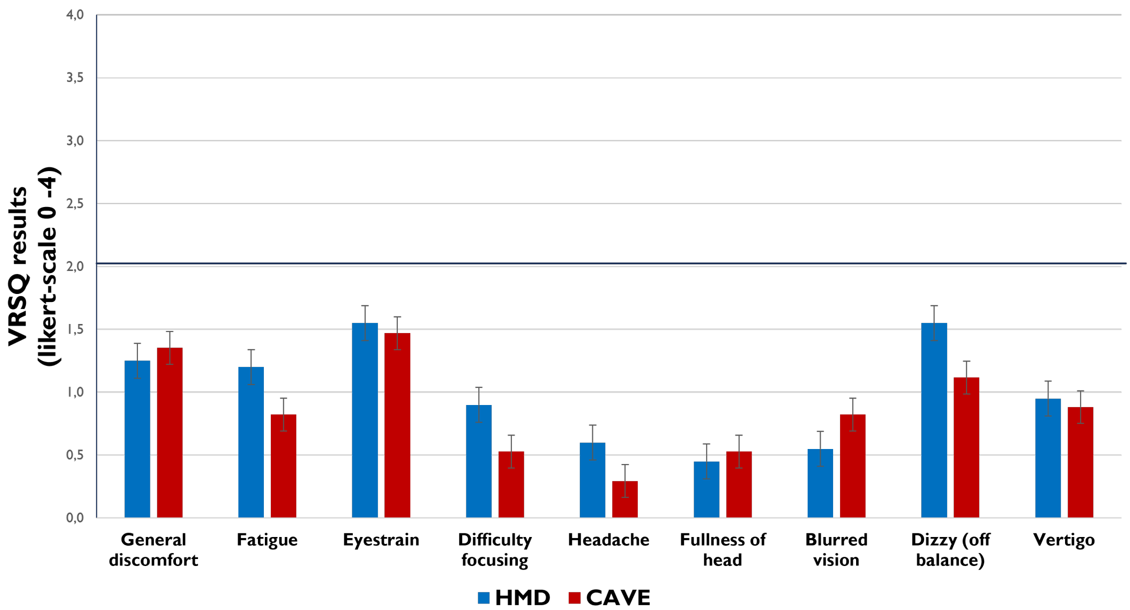


Figure 3.9: VRSQ results

Table 3.3: Mann-Whitney test results for each item of the VRSQ

Item	General discomfort	Fatigue	Eyestrain	Difficulty focusing	Headache	Fullness of head	Blurred vision	Dizzy	Vertigo
U	105.5	95.5	113.5	118.5	127	120.5	104.5	102	105.5
P-values	.402	.224	.590	.724	.985	.780	.381	.341	.402

Application data

Three different data were collected from the application during the experiment: the time needed to complete the task, the users' position in the VE every 0.2 second, and the head rotation angle every 0.2 second.

A Mann-Whitney test on time completion highlighted differences between the CAVE ($M = 795s$) and the HMD ($M = 616s$), $U = 91.5, p = .034$. As expected, participants needed more time to complete the trials with the CAVE. Each modalities total amount of movement in the virtual environment was calculated. A Mann-Whitney test did not show any significant differences between the CAVE and the HMD ($M_{CAVE} = 453.2$m, $M_{HMD} = 414$m), $U = 117, p = .178$. User's virtual movements were drawn on a 2D representation, but no conclusion could be drawn from these data, see Figure 3.11. It was noticeable that some users could easily find their path and orient themselves in the environment, while other participants had more difficulties. To understand their motion strategy, a correlation test was run to compare their background in VR tools or video gaming. However, no correlations were highlighted.

Last, a Mann-Whitney test was performed on head rotation angles. After summing up the absolute rotations made by the participants' heads throughout the experiment, no significant differences were found between both VR systems, $U = 143, p = .486$. At last, the participant looking side was checked (i.e., whether their gaze was rather oriented to the right or the left). Fourteen out of the seventeen participants looked mainly to the right side in the CAVE modality, whereas nine participants did so with the HMD.

Participants' head rotations tend to vary less with the CAVE, with 82% of the participants always looking to the right side against 53% with the HMD. It could have different explanations, such as the ease of turning to the right side with a controller for right-handed people, though; unfortunately, the participant's dominant hand was not recorded. Another explanation could be the possibility for the user to see his hand in the CAVE while, in the HMD, only the controller was visible. Visualizing the hand may be an incentive to look in the corresponding direction, which would then require implementing the users' hand avatar in the HMD.

All the above result are depicted in Figure 3.10.

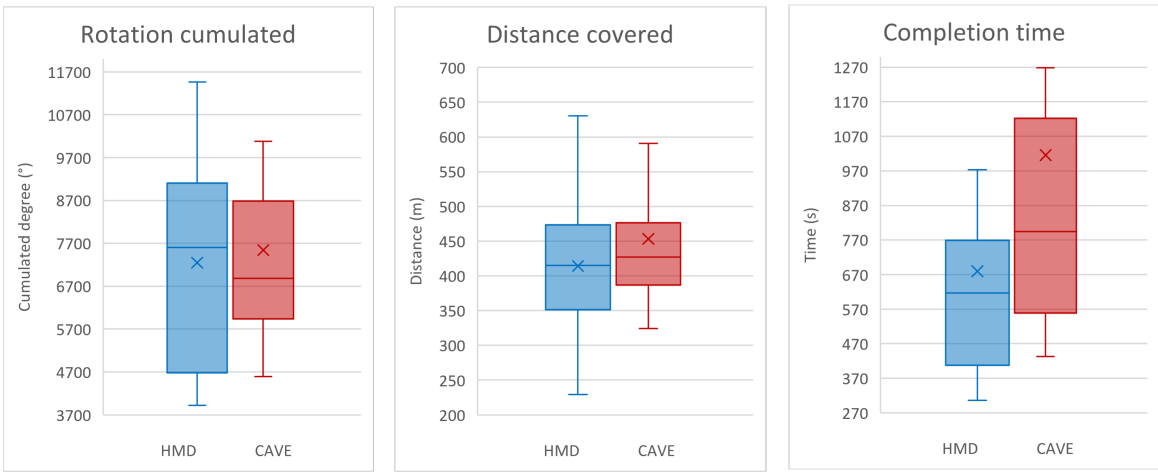


Figure 3.10: Left : Cumulated degree by modality (degree), center : Cumulated distance by modality (meter), right : completion time by modality (second)

User feedback

At the end of the experiment, participants were asked the following question: "If you had to redo the application with the same interaction, would you rather use a CAVE system or an HMD? and why?". For the first part of the question, twelve participants would use the HMD, two participants the CAVE, one answered "it does not matter", seven participants did not respond (four of them did not try both, two of them did not spend enough time to answer, thus they were removed for data analysis). It confirmed hypothesis H2. Similar reasons against the CAVE system came back several times, for instance, the fact that "controls are harder with the CAVE", despite that controls in either the CAVE or the HMD were the same, or "we can see the screens' boundaries", "it is easier with the HMD to look around", coming along with "I tried to limit rotations because it is unpleasant". One participant made an interesting comment about the CAVE, as it emerges from a difference between both devices: "the mix between the virtual environment and reality is complicated to grasp". Comments in favour of the CAVE were that participants were not shielded from reality; they felt less constrained than with the HMD, which fits the finding of [Kwok et al., 2018]. The cons about the HMD relate to the screen resolution limits or the fog on lenses (partially because participants wore face masks against the Covid). Such observations could originate from the fact that HMDs got much more popularized than CAVEs, resulting in a possibly better acceptance of HMDs.

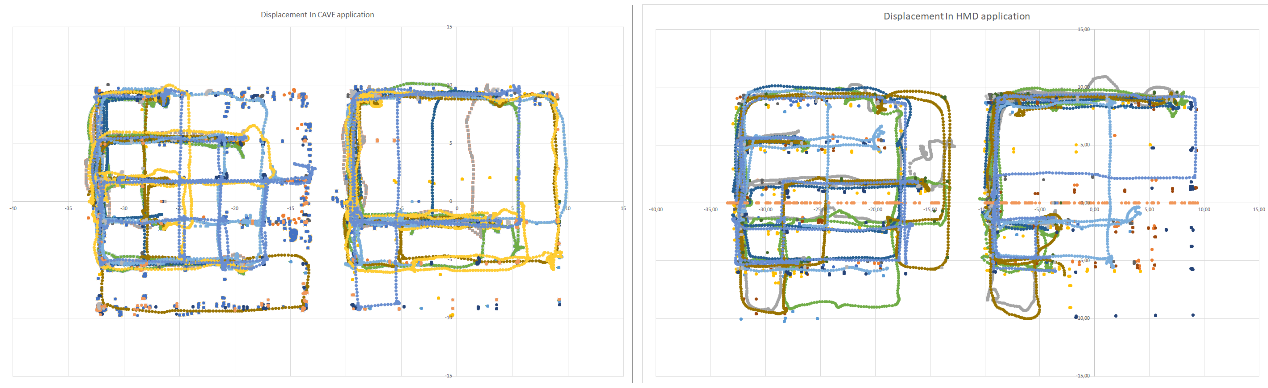


Figure 3.11: Left: Participants movement in the CAVE. Right: Participants movement with the HMD.

3.3.5 Discussion and Limitation

No significant differences could be observed between both systems, contradicting H1 and H3. These results were not expected, as the differences between both VR systems are likely to induce divergences in perception, navigation, rotation or cybersickness as had been found by [Renner et al., 2013, Ghinea et al., 2018, Marsh et al., 2014]. Though, the CAVE modality leads to slightly worse results in the VRSQ and the MISC than the HMD condition. Similarly, the devices seem not to influence the heart rate and rotational movements. This could mean that for the same application displayed on both systems, there is no impact on user behaviours. This statement is limited to a VE developed with the same characteristics as ours and the same environment.

On the other hand, significant differences in time completion were found; in contrast with earlier findings of [Tcha-Tokey et al., 2017], the task was longer to complete in the CAVE than with the HMD. Since there were no differences in rotation angles or movements, this result could originate from the time taken by participants to orient themselves or to find their position in the VE. Therefore, a CAVE may make the user position in VR more challenging to understand than with an HMD.

Unexpectedly, we did not find strong difference between both devices for rotation angles, heart rate and cybersickness, though cybersickness was slightly higher in the CAVE. Last, as expected, the participants' feedback was undisputed in favor of HMDs, confirming H2.

3.4 Impact of eye-screens distance for interaction distance estimation

3.4.1 Introduction

The eye-screens distance between both devices can't be neglected as seen in the subsection 2.2.1, this difference might impact distance perception. Indeed, different studies had been carried treating of distance misestimation, either in real life or using virtual reality devices [Renner et al., 2013, Marsh et al., 2014, Ghinea et al., 2018], highlighting that the vergence-convergence conflict happening with VR devices might play a role in the distance estimation, especially using HMD.

Past research has assumed a positive impact of 3D modelling fidelity to the real world or the presence of different visual cues on distance perception [Renner et al., 2013, Ooi et al., 2001, Park et al., 2021]. Thus, the developed virtual environment reproduced an office in our university (see Figure 3.12). Moreover, the interaction metaphor implemented was straightforward to allow participants to focus on the distance rather than the interaction itself. The office furniture was modelled according to the real one in terms of size and room arrangement. In order to move the object the participants had to use the controller, a simple trigger button was used to pick up the object, releasing the button release the object. Participants had to shift a cube from left to right, according to a distance specified by the experimenter, by pressing the trigger button of the interaction device (either the Flystick device in the CAVE system or the controller of the HTC Vive Pro). In this experiment, we compared interaction in virtual environments using a CAVE and an HMD, considering a simple interaction in the arm's range. The metric used is distance estimation.

3.4.2 Research questions and hypotheses

- Screen-eye distance: HMD's screens are much closer to the eyes and the accommodation distance is fixed, while CAVE's screens accommodation varying. Therefore, to which extent this eyes-screens difference impact distance perception in close range?
- By applying past research results on VR development for improving distance estimation, will distance underestimation significantly decrease?

The answer to these questions will help us to answer our research questions. Depending on the results, some types of interactions may not be easily reproducible from one device to another. If differences appear, they could be counteracted during development. For example by changing the size of the objects, or by increasing or decreasing the ratio of real motion compared to virtual motion (e.g. for example, the user moves his arm 15 cm in real life, but it is scaled up to 20 cm in virtual reality). The following hypotheses were made:

H1. The HMD will induce a higher underestimation of distance than the CAVE due to the visual conflict brought by the eye-screen distance.

H2. Distance underestimation will be less significant than in past research due to an accurate 3D modelling environment and the presence of visual cues.

If distance underestimation is lower but still exists finding from past studies will be confirmed; conversely, if no significant difference between the aimed distance and the one achieved by participants is observed, either the results from past literature experiments could not be replicated, or they are not as significant as announced. Whatever the results found, this experiment may help to better characterize distance estimation errors with more recent technologies than the ones considered in past work. In that sense, technological improvement, such as increased resolutions, lower data transfer delays, an increase of the FOV or lower HMD's weight, should improve user perception without modifying or applying changes to virtual environments.

3.4.3 Experiment design

Participants

21 participants (mean age= 25 ± 15, 5 females) were recruited from different backgrounds inside and outside the university. They were all requested to be free for at least one hour to participate. Upon arrival, they were asked to sign a consent form and fill in a short demographic form.

During the whole experimentation, hand sanitiser was available to the participants. The devices (HMD, controllers, glasses) were systematically disinfected after each use. The experimenter kept wearing a mask during the entire process, however, the participants were allowed to remove their mask when using devices.

Protocol

Participants were taken to the first modality, either in the BlueLemon (modality “C”) or in a room with the HTC Vive (modality “V”). They were introduced to the application illustrated in Figure 3.12, the tasks to be performed and how to interact in the virtual environment. In each modality, participants were given a few minutes to familiarize themselves with the environment, the interaction device and the interaction metaphor. In the HMD modality, we asked them to adjust the IPD according to their view. We also told them that the virtual environment accurately matched a real environment in terms of size, indicated the size of the cube they were to interact with (5 cm) and the table on which the cube was placed (1.20 m). This information was repeated after changing the VR system (“C” or “V”). Following an oral indication, participants had to move the cube 15, 50 and 80 centimeters to the right from the initial position, 18 times under one modality (either C or V) and 18 times under the other modality. The order of distances and modalities was counterbalanced. After each trial, the travel distance was recorded. After completing all trials, which took approximately five minutes, participants were taken to the second modality.

Figure 3.12: Left: Real office used as model for the virtual environment. Right: Virtual scene developed under Unity3D for the CAVE and the HMD.

3.4.4 Results: Interaction distance estimation

The experiment is a 2×3 within-subjects design. The first factor is the modality, with two levels: HMD (V) and CAVE (C). The second factor is the distance, with three levels: 15, 50, and 80 centimeters. The dependent measure, error to target distance (in percentage), was calculated as the average of the 3 trials performed (per condition and modality). The means and standard errors are displayed in Table 3.4.

Table 3.4: Experiment 2 mean and standard error for the distance error in percentage for the modality×distance

	HMD			CAVE		
	15cm	**50cm**	**80cm**	**15cm**	**50cm**	**80cm**
mean	22.87	-8.26	-7.43	22.16	-6.22	-7.09
std. error	4.08	1.64	1.91	3.83	3.11	1.89

Concerning the statistical analysis, two data points were considered outliers, as assessed by examination of studentized residuals for values greater than ±2.75. Outliers were removed from the positional data and replaced with the group means before analysis, following other researchers' works. Data were normally distributed as assessed by Shapiro-Wilk's test of normality on the studentized residuals ($p > 0.05$). Therefore, a two-way repeated measures ANOVA was performed to first determine if an interaction effect exists (see Figure 3.13). Mauchly's test of sphericity indicated an assumption of sphericity for the two-way interaction ($\chi^2(2) = 2.06, p = 0.357$).

The results show no significant interaction effect between the distance and the modality ($F(2, 40) = 0.27, p = 0.767$). We analysed the main effects. No significant main effect of the modality was present ($F(1, 20) = 0.89, p = 0.769$). Mauchly's test of sphericity indicated that the assumption of sphericity had been violated for the distance factor ($\chi^2(2) = 11.54, p = 0.003$). The Huynh-Feldt method was used to adjust the results. There was a significant main effect of the distance ($F(1.44, 28.44) = 50.65, p < 0.001, \epsilon = 0.721$) on participants' exocentric distance estimation. Pairwise comparisons with Bonferroni correction show that there is no significant difference between 50 and 80 centimeters ($p > 0.05$), but a significant difference was found between 15 and 50 centimeters ($p < 0.001$), and between 15 and 80 centimeters ($p = 0.001$).

3.4.5 Discussion and Limitation

Distance estimation between two radically different VR systems has been compared after the development of an immersive application based on past work [Kelly et al., 2017, Renner et al., 2013, Willemsen et al., 2004]. Strong underestimation for short distances (15cm), either in the CAVE or with the HMD was shown, which supports the results from past research [Renner et al., 2013]. This underestimation reduces when the distance rises up to 80cm ($M_{15cm} = -24.22\%, M_{50cm} = -6.19\%, M_{80cm} = -7.\%$), according to findings. This result is in line with the research of [Vienne

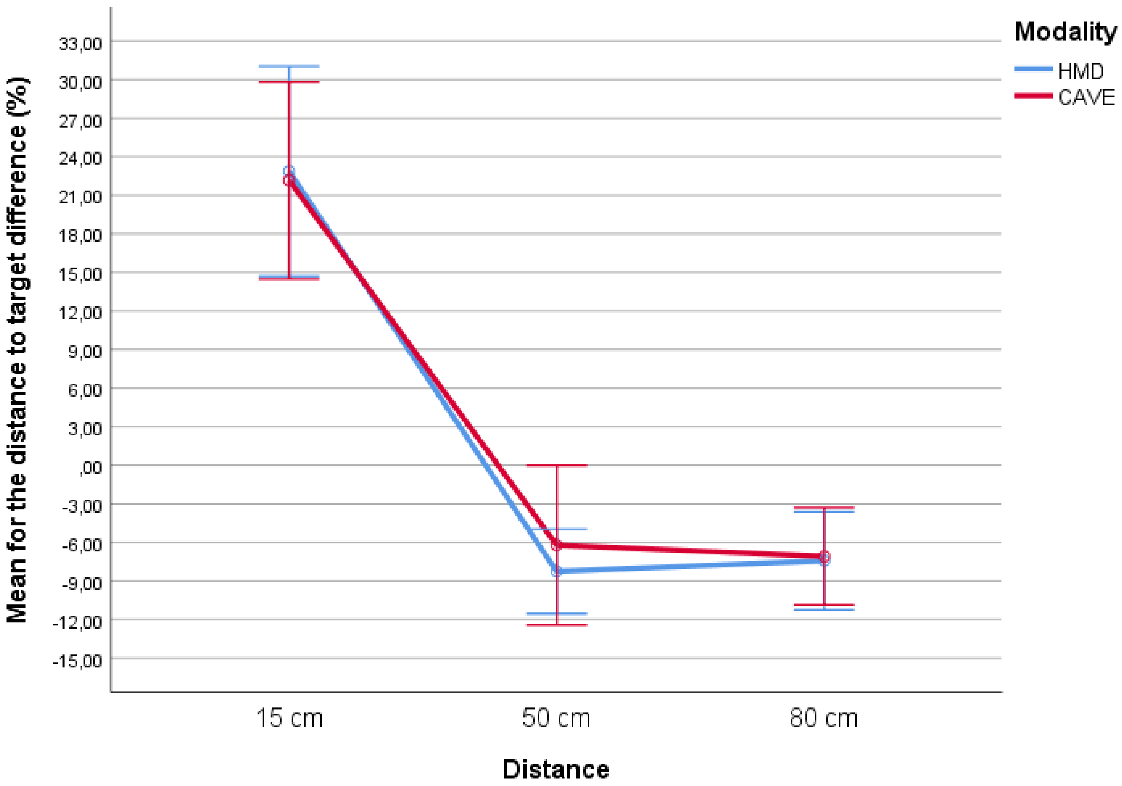


Figure 3.13: Experiment 2, distance to the target (in percentage). The mean and standard error for each modality and target distance

et al., 2020], although other authors found opposite findings [Lin et al., 2019]. Interestingly, between both VR systems, no significant differences were observed, which might mean that no matter the condition, short distances are harder to reproduce accurately. Furthermore, by faithfully modelling a real-size environment with a medium rich visual cues environment, distance underestimation might be reduced in a virtual environment which is in line with previous studies [Kenyon et al., 2008, Renner et al., 2013]. These results support the hypotheses that distance underestimation will be less significant with recent hardware and the use of cues. These results cannot be generalized and only apply to interaction in arms range in a moderate visual cue-rich environment. Partially answering the research questions, the difference in eye-screen distance between the HMD and the CAVE has no impact on distance perception, for an arm's reach interaction, with the 3D model rendered in front of the screen. In addition, previous research had an underestimation of 26%, smaller error for distances greater than 15 centimetres appear in this study, then, not using an empty 3D environment and newer technology can improve distance perception.

There is some limitation to this study. multiple trials were conducted over a short duration, and the break time between blocks of different conditions was relatively short. Moreover, participant's dominant hand has not been recorded.

3.5 Which device to use to limit cybersickness

3.5.1 Introduction

As seen previously, cybersickness is still an important issue when using VR devices. Past studies reveal lower effect in CAVEs [Kemeny et al., 2020, Polcar and Horejsi, 2015]. In comparison of [Polcar and Horejsi, 2015], the CAVE-like system used is a one-wall CAVE, reducing the optic flow compared to CAVEs with more walls, thus reducing the possible negative effects of such displays. They found overall more symptoms in CAVEs, but more severe with HMDs. As already stated, avatar visualization might help to reduce cybersickness [Kemeny et al., 2020]. HMDs optical flow is smaller due to the smaller FOV, and the body is not visible, whereas, within CAVEs system the body is visible but the FOV is wider. Thus both displays present positive and negative features related to cybersickness. As the objective was to compare both devices without interfering in the characteristics, we did not have any avatar in the HMD application.

3.5.2 Research questions and hypotheses

- Does optical flow have higher impact on user cybersickness?

Cybersickness is known to impact user experience, and both displays present different features that might induce or reduce cybersickness symptoms. This experience allows us to bring an element of answer to our first research question *Which are the device's characteristics that might affect users' experience while executing a particular task?*, here, for a forest walk application, with sliding as a movement metaphor. We made the following hypothesis for this experiment:

H1. Higher optic flow in the HMD will lead participants to experience more cybersickness symptoms than in the CAVE system.

The visualization of the body in CAVEs would not overcome the higher optic flow compared to HMDs, which would lead to a higher cybersickness level in the former (i.e., CAVE system).

To assess this hypothesis, we carried an experiment with both devices. To this end, we have developed a walking application in a virtual forest. In order to compare our two devices, we made sure that the two experiences were as similar as possible. The participants had to enter the virtual environment, then they were guided within the VE. No interaction was possible during the application, they only had to follow a fairy with their eyes (see Figure 3.14), thus guiding their gaze. The walk lasted 12 minutes and 30 seconds. The application has been designed not to reduce the harm of the simulator, while remaining a plausible use case for a VR application. In fact, the user slided on the ground (as if he was using a joystick), he crossed different environments, forests and buildings, navigation also accelerated along the way.

Figure 3.14: The fairy and environment developed for the experiment on cybersickness

3.5.3 Experiment design

Participants

47 participants (mean age= 27 ± 5, 16 females) participated in this experiment, They were from different background and experience with VR tools (13p: < 5h, 3p: 5h-10h, 3p: 10h-20h, 16p: > 20h). To participate they were able to register by mail and we requested them to be available during one hour upon arrival.

Protocol

The following protocol was followed identically with the CAVE and the HMD. The two modalities were done in two different locations two weeks apart. Once arrived in the experimental room, a consent form was presented to participants to inform them of the experiment. Once accepted and signed, we put the E4 wristband on their wrist. After set up, the wristband was turned on to get a baseline of each participant's heart rate, and we asked them to fill a demographic questionnaire (Surname, First name, Age, Sex, VR experience). Once the questionnaire filled, we performed a first postural balance test, in order to have participants' postural stability prior VR exposure, thanks to the Win-Posturo device[2].

Then we led them to the experimental room (CAVE or HMD), we presented them the application and the device for those that never saw it before, we explained them the task to perform during the whole experiment (i.e., just follow the fairy), we specified not to move their body and that they were free to stop at any moment if they felt the need. For the HMD modality, we asked them to set the IPD according to their view. Then they did the forest walk and stayed 12 min 30 seconds in the application (time needed to do a whole lap in the forest, see Figure 3.15). Each participant did the experiment once with one system or the other. As soon as they finished the application we did another postural recording, we asked them to fill two questionnaires, the VRSQ and the Slater-Usoh-Steed (SUS) questionnaires. Before leaving we proposed drinks and made sure they felt well.

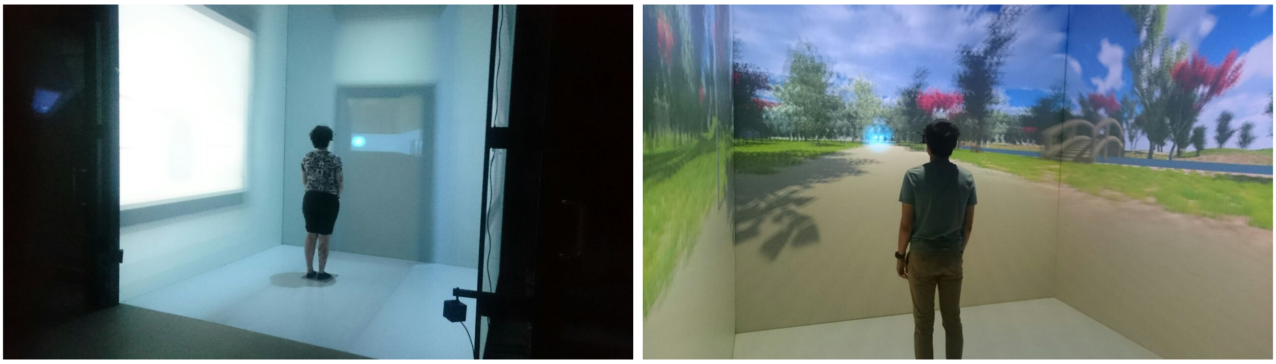


Figure 3.15: The two types of virtual environment, seen through the CAVE of CRVM. Left: inside a building / right: in the forest

3.5.4 Results: Which device to limit cybersickness

For all the data collected, we performed normality checks. According to sample size, normality check and data analysed t-test, Mann-Whitney or Wilcoxon Signed-Rank tests were performed. The significance threshold was set to .05.

Heart Rate: First, normalization was applied to be able to compare HR between participants. A

[2]https://www.medicapteurs.com/fr/produits/

Mann-Whitney test revealed that heart rate was significantly higher with the HMD ($M = 0.491, SD = 0.043$) than with the CAVE ($M = 0.607, SD = 0.031$), $U = 107, p = .028$.

Postural stability (PS): We extracted the length of displacement of the participants' center of gravity (in millimeter) and its speed (in millimeter per second), both parameters being related to the participants' postural stability, which itself is an indicator of possible symptoms of cybersickness. Length and speed for the CAVE modality followed a normal distribution, thus we applied t-test for paired samples. The results from the pre-test ($M = 207.82, SD = 9.306$) and post-test ($M = 214.83, SD = 9.61$) for the displacement length indicate that exposure to VR does not decrease postural stability, $t(18) = 2.1, p = .389$. There was no significant increase either regarding the speed after exposure ($M = 0.364, SD = 0.377$) compared to the test before exposure ($M = 8.13, SD = 8.383$), $t(18) = 2.1, p = .437$. In the HMD modality, a Wilcoxon signed-ranks test indicated that results for pre- vs. post-length ($Z = 2.87, p = .001$) and speed ($Z = 2.921, p < .000$) were not significant.

Questionnaire: A Mann-Whitney test between modalities on VRSQ results did not show any significant differences between both hardware, $U_{VRSQ} = 166, p = .916$. An analysis of each VRSQ item also failed to show differences (see Table 3.5).

	General discomfort	Fatigue	Eyestrain	Difficulty focusing	Headache	Fullness of head	Blurred vision	Dizzy	Vertigo
U	155	202	174.5	206	193.5	157	166.5	204	182
P-values	.662	.341	.892	.283	.478	.706	.916	.311	.729

Table 3.5: Mann-Whitney test results for each item of the VRSQ

Both total means of SUS followed a normal distribution, we applied a t-test between our two groups, the results from the CAVE SUS ($M = 4.45, SD = 0.182$) and HMD ($M = 4.105, SD = 0.265$) did not reveal any significant differences, $t(32) = 2.036p = .292$.

Feed-back: Participants' feedback mention their preference for the wide environment, and the difficulties encountered inside the building. They all perceived an increased speed inside the building (while the speed was actually slowed down), moreover most of them made the remark that "inside the building, is was unpleasant, or less pleasant than outside". This is in line with past research, that narrow environments increase cybersickness, and is more uncomfortable for users.

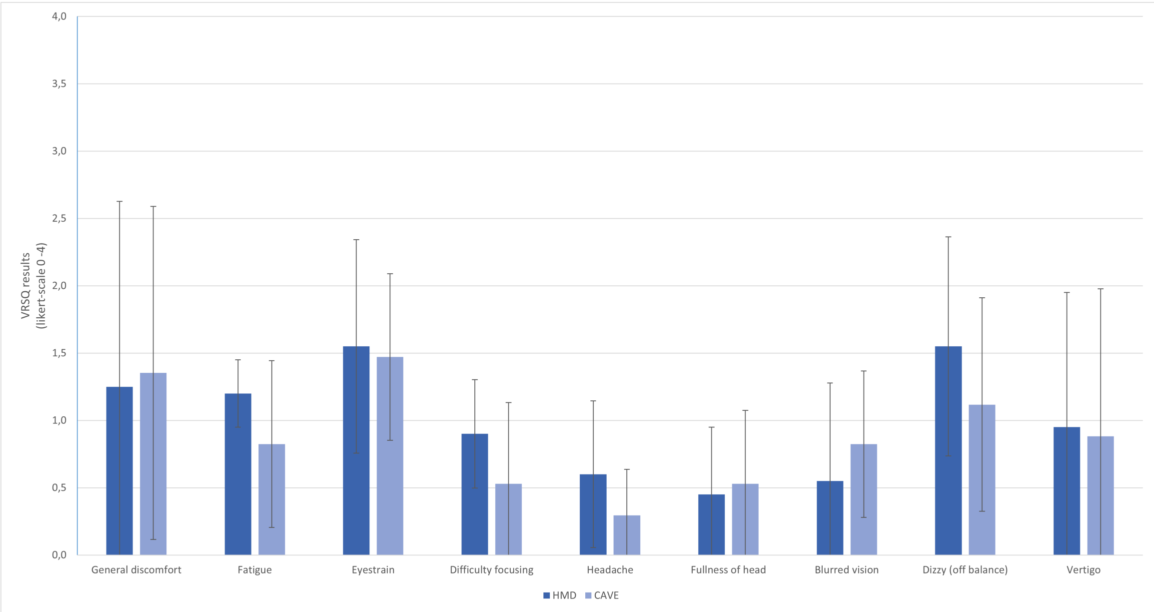


Figure 3.16: VRSQ results

3.5.5 Conclusion

Despite an application developed to induce a simulator sickness, we failed to get any meaningful symptoms. As the protocol is between subjects, we cannot say whether participants preferred one device over the other. Nevertheless, with both devices, we noticed a discomfort during the passage in the buildings. At this moment the optic flow is higher, validating part of our hypothesis: higher optic flow induces more cybersickness.

3.5.6 Discussion and Limitation

Although this is surprising, we note that we may not have enough participants. We tried to induce cybersickness and failed. The recent technical improvements of the devices may contribute to less severity of cybersickness effects. Another possibility is that the technology is more accessible, and people are less and less naive to these technologies, and therefore less sensitive to the effect of the simulator.

3.6 Conclusion

With respect to our two main research questions: *Which device features affect user experience when performing a particular task?* and *Is it possible to have a similar user experience with these two technologies?*, we presented four experiments to compare CAVE and HMD systems. All focused on specific features of the systems that could impact user experiences according to literature review. Our experiments provide part of the answer. We wondered the following questions and got the following results.

When using a CAVE, we wear only a pair of light glasses, while when using an HMD, we wear a helmet with a possibly significant weight. Therefore, does the device's weight significantly affect perception and to which extent?, our results do not show differences between the two displays, we observed a significant difference between the aimed distance and the distance done above three meters, which we do not consider crucial for usual usage of our devices. Bringing an element of answer to our research question, the weight of the helmet does not influence the user experience, at least not in the use cases we are interested in.

The second question was *if the same theoretical virtual environment is offered with both systems, will the divergences in FOR and FOV significantly impact user perception and the way users navigate in a virtual environment?*. Results failed to highlight differences in navigation and cybersickness, while they showed significant higher time completion for the CAVE and a unanimous preference for the HMD system. The majority of users preferred the HMD, and from our protocol we suppose that this is due to the FOR difference.

Two questions were drawn for the next experiments: *HMD's screens are much closer to the eyes than CAVE's screens. Therefore, to which extent this eyes-screens difference impact distance perception in close range?* and *By applying past research results on VR development for improving distance estimation, will distance underestimation significantly decrease?*. According to our data, no significant difference was found, both software follows the same curve: distance is strongly underestimated for short distances and the accuracy improves with the size estimated.

The question for the last experiment was *Does optical flow have higher impact on user cybersickness?*, once again we failed at showing differences, no system induces more cybersickness than the other. Interestingly, without trying to reduce cybersickness, none of the two devices provoked it, we even got good results from VRSQ ($M_{CAVE} = 1.0, M_{HMD} = 0.87$).

Conclusion

General discussion

Users' behavior and how they experience virtual reality are still not really understood, and we are facing a rising amount of display types allowing people to get in virtual environment. Hence the pros and cons of these devices are not determined, and we can rightfully wonder why using one device instead of another. The differences that define these display's might impact user behaviors and experience, by impacting their visualization of the VE, their behavior for interaction or navigation. To address these issues we carried out four experiments to compare two specific devices which were CAVEs and HMDs.

One experiment was performed for each point extracted as fundamental differences: one sought the differences in device worn weight. The results show that the distance is overestimated beyond three meters, and the weight of the HMD itself can have an impact on the distance travelled. However, alone, this factor does not explain the underestimation seen in the studies. This device difference may not be taken into account as impacting the user experience for distances less than three meters. A second explored the difference between the field of view (FOV) and the field of regard (FOR). Surprisingly, no significant differences between the two devices were found for rotation angles, heart rate and cybersickness. However, the task completion time was shorter with the CAVE device, and participants' feedback was in favour of using HMDs. Therefore, for an application requiring regular point of view rotations, HMDs are to be preferred. A third experiment focused on the difference between eyes-screen distances. The results show no significant difference between the two devices. However, an overestimation was observed for the 15 cm distance, confirming the difficulty of correctly perceiving short distances through virtual reality tools. A last one focused on cybersickness; this factor is a well-documented field with HMD devices but not that much with CAVEs.

Our research questions and the objective of this work were to compare two different virtual reality displays through the user experience. In this regard, our main questions were:

- **Which are the device's characteristics that might affect users' experience while executing a particular task (e.g., navigation or manipulation)?**
- **Is it possible to have a similar user experience with these two technologies?**

In other words, what are the features of the devices that affect the user experience and have an impact on it?, and can this difference be overcome through application or practice? The experiments developed are all focused on a specific aspect differentiating CAVEs and HMDs, for which previous studies have shown could impact on UX, while limiting any bias that might arise from another factor.

Scientific contributions and guidelines

This work's significant contributions summarize as follows:

CAVE and HMD comparison: In our review, we found few papers that compared CAVEs and HMDs, or that gave a detailed analysis of these two devices. This work can help researchers who would like to study this topic to get an overview of the different limitations of the two technologies, their common and divergent points. In this way, we provide an interesting research basis for dealing with the subject.

Walking with VR devices: We conducted an experiment on the perception of walking distances. Our results show that for a physical displacement of less than three meters, there is no significant difference between HMDs and CAVEs. At least, this distance will not be induced by the weight of the immersive helmet. It is important to note that most of the setups used for virtual reality applications, whatever whether it is the area reserved by users with HMDs or the size of common CAVEs, rarely exceed nine square meters. This result, although not applicable to all use cases, can be used in a large majority of use cases.

Navigation in VE: While we expected to see differences in behaviour for a navigation task in a large environment, and moreover, with a task that required the user to rotate a lot to look around, we were surprised to find that there was no significant difference between the two devices, although one of them seemed to be better suited to this type of application. We have only noted a difference in the time required to complete the task. The CAVE therefore requires more time to complete the same task. In addition, the participants objectively preferred the use of the immersive headset. With no significant difference in terms of rotation or cybersickness, but with a shorter time and a user's preference for HMDs, it would be more interesting to use the latter for large environment exploration applications.

Egocentric distance: Again, we found no significant difference between our two devices. It is however worth noting that short distance perception is complicated to reproduce (in our case if the distance is less than 15 cm, a significant difference appears in our two conditions). We limit our results to a perception of distance for relatively small objects ($\approx$ 5 cm), a displacement between 15 and 80 cm and a distance lower than 1 m.

It is interesting to see that we were unable to reveal significant differences between our two devices, despite the experiments that aimed to highlight differences that would appear due to the technical differences between our two virtual reality tools. Moreover, these differences should have had a significant role on the user experience according to the previous study.

Limitations

Our different experiments have several limitations.

First of all they are all limited to strict use cases. We cannot generalize our results. They were all conducted during a pandemic period, therefore with a compulsory wearing of a mask, which could have had an impact on some measures. Because of some technical problems, on the application development side but also of the availability of the hardware we had to use two different CAVEs, and some applications could have been visually improved.

The most important limitation comes from our initial decision to isolate our factors. By trying to isolate our settings to see if they impacted the user experience independently of the rest, we did not take into account that even if they did not independently modify the user experience, the accumulation of different factors could have an impact. Thus, our application protocol and development would have caused to have no significant difference.

Perspectives

The different contributions presented represent the first step in a usability characterization of both CAVE and HMD devices. Thus, we present hereafter, what could be addressed later in order to complete this characterization.

We are willing to continue to compare the two devices, by isolating others factors to see if one of them is a determining factor in the user experience and if it makes one device clearly more suitable for some usages. Thus we would first advise to focus further research on the specific points that we did not address, such as body visualization, image brightness, screen edge visualization or resolution limits (which appeared relatively often in our studies, when using HMDs).

As our studies were conducted with only a few participants (about 20 each time), validation with a larger number may be necessary, specifically for results that were unexpected, such as user behaviour during a navigation task in both devices. Moreover, CAVEs are mainly considered as devices that allow more efficient collaboration or project reviews. Carrying out a clear study on this comparison could be interesting.

In view of our results, it would be interesting in a second time to see the impact of several factors. Maybe certain factors, put together, will allow to put forward differences which, added together, can influence the user experience.

Finally, with the multitude of HMDs and CAVE systems, and their rapid evolution, studies on the features that will evolve faster and their impact on the user experience should be prioritised (e.g., screen resolution is more likely to change than the screen edges visualization).

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Annexe

Chapter 4

Annexes

4.1 Questionnaire for navigation experiment

4.2 Questionnaire for cybersickness experiment

Navigation in building HMD

*Obligatoire

Oculomotor

1. General discomfort / Inconfort général *

Une seule réponse possible.

	0	1	2	3	4	
not a	◯	◯	◯	◯	◯	Very

2. Fatigue *

Une seule réponse possible.

	0	1	2	3	4	
not a	◯	◯	◯	◯	◯	Very

3. Eyestrain / Fatigue visuelle *

Une seule réponse possible.

	0	1	2	3	4	
not a	◯	◯	◯	◯	◯	Very

4. Difficulty focusing / Difficulté à ce concentrer *

Une seule réponse possible.

	0	1	2	3	4	
not a	◯	◯	◯	◯	◯	Very

Disorientation

5. Headache / Mal de tête *

Une seule réponse possible.

	0	1	2	3	4	
not a	◯	◯	◯	◯	◯	Very

6. Fullness of head / Tête lourde *

Une seule réponse possible.

	0	1	2	3	4	
not a	◯	◯	◯	◯	◯	Very

7. Blurred vision / Vision flou *

Une seule réponse possible.

	0	1	2	3	4	
not a	◯	◯	◯	◯	◯	Very

8. Dizzy (off balance) / étourdis, perte d'équilibre *

Une seule réponse possible.

	0	1	2	3	4	
not a	◯	◯	◯	◯	◯	Very

9. Vertigo / Vertige *

Une seule réponse possible.

	0	1	2	3	4	
not a	◯	◯	◯	◯	◯	Very

Other

10. Comments / Commentaire?

Cybersickness experiment

*Obligatoire

Demographic form

1. Nom&Prénom / Name&Surname

2. Gender

Une seule réponse possible.

- Male
- Female
- Autre :

3. Age

4. Experience with VR

Une seule réponse possible.

- < 5h
- 5h - 10h
- 10h - 20h
- > 20h

Virtual Reality Sickness Questionnaire (VRSQ)
At the very moment

Oculomotor

5. General discomfort / Inconfort général *

Une seule réponse possible.

	0	1	2	3	4	
not a	◯	◯	◯	◯	◯	Very much

6. Fatigue *

Une seule réponse possible.

	0	1	2	3	4	
not a	◯	◯	◯	◯	◯	Very much

7. Eyestrain / Fatigue visuelle *

Une seule réponse possible.

	0	1	2	3	4	
not a	◯	◯	◯	◯	◯	Very much

8. Difficulty focusing / Difficulté à ce concentrer *

Une seule réponse possible.

	0	1	2	3	4	
not ;	◯	◯	◯	◯	◯	Very much

Disorientation

9. Headache / Mal de tête *

Une seule réponse possible.

	0	1	2	3	4	
not ;	◯	◯	◯	◯	◯	Very much

10. Fullness of head / Tête lourde *

Une seule réponse possible.

	0	1	2	3	4	
not ;	◯	◯	◯	◯	◯	Very much

11. Blurred vision / Vision flou *

Une seule réponse possible.

	0	1	2	3	4	
not ;	◯	◯	◯	◯	◯	Very much

12. Dizzy (off balance) / étourdis, perte d'équilibre *

Une seule réponse possible.

	0	1	2	3	4	
not a	◯	◯	◯	◯	◯	Very much

13. Vertigo / Vertige *

Une seule réponse possible.

	0	1	2	3	4	
not a	◯	◯	◯	◯	◯	Very much

Slater Usoh Steed
Presence questionnaire

14. Please rate your sense of being in the forest. I had a sense of “being there”.

Une seule réponse possible.

	1	2	3	4	5	6	7	
Not	◯	◯	◯	◯	◯	◯	◯	Very Much

15. There were times during the experience when the virtual envrionement became more real than compared to the “real world”

Une seule réponse possible.

	1	2	3	4	5	6	7	
At n	◯	◯	◯	◯	◯	◯	◯	Almost all the time

16. When you think back about your experirence, do you think of the virtual forest more as an image you saw, or more as as somewhere you visited ?

Une seule réponse possible.

	1	2	3	4	5	6	7	
Imaş	◯	◯	◯	◯	◯	◯	◯	Somewhere that I visited

17. During the time of the experience, which was strongest on the whole, your sense of being in the virtual forest, or of being in the real world of the laboratory?

Une seule réponse possible.

	1	2	3	4	5	6	7	
The	◯	◯	◯	◯	◯	◯	◯	The virtual reality of the forest

18. I think of the virtual forest as a place in a way similar to other places that I’ve been

Une seule réponse possible.

	1	2	3	4	5	6	7	
Not	◯	◯	◯	◯	◯	◯	◯	Very much so

19. During the experience I often thought that I was really standing in the lab wearing a helmet

Une seule réponse possible.

	1	2	3	4	5	6	7	
Mos	◯	◯	◯	◯	◯	◯	◯	Never because the virtual forest overwherlmed n

Other

20. Comments / Commentaire?

Acronyms

- VE – Virtual Environment
- VR – Virtual Reality
- IVR – Immersive Virtual Reality
- VR – Mixed Reality
- CAVE – Cave Automatic Virtual Environment
- HMD – Head-Mounted-Display
- HR – Heart-Rate
- SC – Skin-Conductance
- AEC – Architecture, Engineering, and Construction Industry
- BIM – Building Model Informations
- IPD – InterPupillary Distance
- ODV – Omnidirectional videos
- UX – User eXperience
- FOV – Field of view
- FOR – Field of regards
- SS – Simulator Sickness
- VRSI – Virtual reality-induced symptoms and effects

- MS – Motion sickness
- BCI – Brain-Computer Interface
- CVE – Collaborative Virtual Environment
- LSID – Large-Screen Immersive Display
- SWD – Screen Wide Display

Partie Française

4.3 Resumé Français 10% :

Resumé général :

Le sujet de ce doctorat est "L'expérience utilisateur en immersion virtuelle : une étude des facteurs d'échelle pour une perception similaire dans un CAVE et dans un HMD". Démarré en octobre 2019 dans le cadre d'une cotutelle entre deux laboratoires de recherche, le LISPEN (Laboratoire d'Ingénierie des Systèmes Physiques et Numériques) et l'IMI (Institut für Informationsmanagement im Ingenieurwesen), appartenant respectivement à l'ENSAM (Ecole Nationale Supérieure des Arts et Métiers) en France et au KIT (Karlsruhe Institute of Technology) en Allemagne, ce travail a été réalisé sous la supervision du Pr. MERIENNE Frédéric, Dr. CHARDONNET Jean-Rémy et Pr. OVTCHAROVA Jivka. Cette thèse a pour but de comparer deux dispositifs différents, les CAVEs (CAVE Automatic Virtual Environment) et les casques de réalité immersive. Nous sommes partis de l'affirmation suivante : "Un CAVE et un casque de réalité immersive sont deux technologies différentes permettant toutes deux l'immersion dans un environnement virtuel". Cependant, leurs différences pourraient influencer l'expérience de l'utilisateur. Pour étudier cette affirmation, nous avons posé deux questions de recherche : Un CAVE et un casque de réalité immersive offrent-ils des expériences utilisateur différentes ? Et : 'Est-il possible d'avoir une expérience utilisateur similaire avec ces deux technologies ?'. Nos objectifs étaient d'explorer les différences CAVE-HMD qui pourraient influencer le comportement et l'expérience de l'utilisateur. Pour répondre à ces questions de recherche, nous avons construit des expériences pour nous concentrer sur les différences fondamentales entre les deux dispositifs, c'est-à-dire les différences provenant des caractéristiques du dispositif. Nous avons réalisé quatre expériences sur quatre caractéristiques distinctes.

Le sujet de la première portait sur les différences de poids entre les dispositifs. En effet, le poids

porté peut influencer la distance parcourue perçue lors de la marche ; le poids des HMD varie entre 500 et 1000 g, tandis que le poids des lunettes portées dans un CAVE est inférieur à 100 g ; nous avons donc un rapport de 5 à 10 fois pour le poids porté entre les HMD et les CAVE. La deuxième expérience portait sur la différence entre les distances œil-écran. Avec les HMD, les écrans sont plus proches des yeux (physiquement, optiquement, ils sont à environ deux mètres), mais pour un CAVE, les écrans sont physiquement plus éloignés. En outre, les utilisateurs peuvent se déplacer dans un CAVE et donc se rapprocher ou s'éloigner des écrans, ce qui modifie la façon dont est rendu l'objet virtuel par rapport à l'écran (c'est-à-dire derrière l'écran, sur l'écran ou devant). De plus, notre cerveau utilise des indices visuels et des réactions oculaires telles que l'accommodation et la vergence pour estimer les distances ou les tailles, ainsi cette distance yeux-écran peut influencer la perception. La troisième expérience a eu pour but d'explorer la différence entre champ de vision (FOV) et champ d'observation (FOR). Pour les HMD, nous avons un FOR de 360° et un FOV de 110°, en moyenne, contre 270° (ou moins) pour les CAVE et jusqu'à 220° de FOV. La rotation de la tête dans les CAVE en est donc limitée, ce qui rend plus difficile certaines tâches, comme l'exploration d'un environnement étroit qui demande aux utilisateurs de regarder autour d'eux et de tourner souvent leurs vues, ce qui peut influencer l'expérience et le comportement des utilisateurs. Le mal du simulateur a été le facteur étudié pour la dernière expérience, celui-ci est un domaine bien documenté avec les dispositifs HMD, mais pas autant avec les CAVE. A notre connaissance, aucune étude n'a comparé les deux systèmes sur ce sujet spécifique. Nous avons développé une application pour induire un certain niveau de cybersickness afin de comparer les deux dispositifs. Nos résultats ne montrent aucune différence significative dans la distance de marche perçue pour des distances allant jusqu'à trois mètres. Par conséquent, le poids du HMD, qui est négligeable dans le CAVE, peut être ignoré pour une application qui ne nécessite pas de déplacement physique au-delà de trois mètres, ce qui est valide dans la grande majorité des cas d'usage de ces dispositifs. Les courtes distances dans le cas d'un déplacement d'un objet sont plus difficiles à évaluer, quel que soit l'appareil, mais les deux présentent des résultats précis pour les distances plus longues. Il est intéressant de noter que nous n'avons pas trouvé de différence significative dans la rotation de la tête entre les appareils, alors que, pour la tâche conçue, les participants ont mis plus de temps à terminer l'application complète dans le CAVE. Nous supposons que cette variation de temps pourrait provenir du temps pris par les participants pour effectuer la rotation dans le CAVE. Les commentaires des utilisateurs sont unanimement en faveur des casques. L'utilisation du HMD est plus naturelle, ils peuvent tourner la tête, les contrôles sont plus maniables, et le fait que les limites physiques soient visibles a été un point perturbant pour le deuxième affichage pour certains participants. A partir de ces résultats, nous fournissons des conseils et une ligne directrice sur le dispositif à utiliser en fonction des besoins de l'application en termes de navigation, d'interaction ou d'expérience utilisateur (temps de réalisation, sentiment, motivation, cybersickness)

Motivation :

La réalité virtuelle est en plein essor depuis plusieurs années. La disponibilité de nombreux outils de développement d'applications et de visualisation à faible coût (par exemple, des casques immersifs comme l'Oculus Quest ou le HTC Vive) a permis de démocratiser la réalité virtuelle dans de nombreux domaines, tels que la conception de produits, la revue de projets, la santé, la construction et la formation. De plus, les avantages d'inclure cette technologie sont clairs : une étude publiée en 2018 par Capgemini montre que parmi 700 entreprises, 75% d'entre elles avaient augmenté leurs bénéfices opérationnels de plus de 10% en utilisant la réalité virtuelle dans leurs processus[1].

Bien que les premiers développements de la réalité virtuelle remontent aux années 1960, plusieurs barrières scientifiques subsistent pour parvenir à une diffusion massive de ces technologies. En effet, il est nécessaire de disposer de plus d'informations pour comprendre pleinement le comportement des utilisateurs et la manière dont ils vivent la RV. De plus, la variété des dispositifs de visualisation, tels que les écrans 3D, les casques immersifs et les salles immersives (CAVE), rend le traitement de ces obstacles plus complexe. En effet, le comportement et l'expérience des utilisateurs dans une RV peuvent être affectés, entre autres, par le type d'affichage, le temps d'exposition, le contenu et l'objectif de l'application, le profil des utilisateurs, leur expérience antérieure et leurs attentes vis-à-vis de ce type de technologie. De plus, le cybersickness, qui est un phénomène induisant des effets indésirables tels que la fatigue oculaire, la fatigue visuelle, les maux de tête ou les nausées, et qui apparaît principalement lors de tâches de navigation virtuelle, est l'une des principales limites qui empêchent les utilisateurs d'utiliser la RV confortablement. De nombreux travaux ont cherché à comprendre et caractériser ce phénomène afin d'en réduire les effets [Chardonnet et al., 2017, Aykent et al., 2014]. La façon dont les utilisateurs interagissent dans la RV est une autre clé importante pour comprendre comment ils perçoivent les environnements virtuels. Par exemple, lors d'une tâche de navigation, certaines

[1] https://www.capgemini.com/news/press-releases/immersive-technology-has-arrived-ar-and-vr-set-to-become-mainstream-in-business-operations-in-the-next-3-years/

technologies ne permettent pas de se déplacer librement dans les VE ou nécessitent l'utilisation de techniques de navigation qui sont souvent peu naturelles et difficiles à appréhender. Enfin, certains auteurs ont montré que la perception des utilisateurs dans les environnements virtuels pouvait différer en fonction des dispositifs utilisés [Aykent et al., 2014, Dorado et al., 2017, Marsh et al., 2014, Tcha-Tokey et al., 2017].

Afin d'aborder ces questions, l'objectif principal de ce travail est d'étudier les principaux facteurs pouvant influencer l'expérience utilisateur pour deux dispositifs de visualisation différents, les CAVE et les casques immersifs.

L'affirmation suivante a été faite : **"Un environnement virtuel automatique CAVE et un casque de réalité immersive sont deux technologies différentes permettant l'immersion dans un environnement virtuel mais présentent toutes deux des dissemblances"**. Cela a conduit à deux questions de recherche principales :

- **Quelles sont les caractéristiques de l'appareil qui pourraient affecter l'expérience des utilisateurs lors de l'exécution d'une tâche particulière (par exemple, la navigation ou la manipulation) ?**
- **Il est possible d'avoir une expérience utilisateur similaire avec ces deux technologies?**

Contexte de recherche:

Les termes de réalité virtuelle, réalité mixte et réalité augmentée sont connus depuis un certain temps. Les chercheurs du passé ont essayé de donner des définitions précises, mais selon le secteur et l'application qui utilise la technologie, certaines variations existent [Muhanna, 2015]. De plus, ces définitions ont évolué au fur et à mesure des changements technologiques. Pour commencer, nous donnons la définition des différents termes employés dans ce manuscrit et qui se rapportent à notre sujet d'étude : l'expérience utilisateur en réalité virtuelle pour différentes technologies d'affichage.

Les environnements virtuels permettent de créer des situations spécifiques de la vie réelle. Cela est particulièrement important pour la simulation de conduite, la recherche industrielle, les compétences sociales humaines et l'analyse du comportement des piétons. En ce qui concerne la formation, la RV réduit les risques pour les participants et permet de recueillir davantage de données. Par exemple, les systèmes de RV permettent de suivre la trajectoire exacte des utilisateurs pendant la locomotion et d'obtenir des données sur le regard. Les RV sont couramment utilisées dans le domaine de la simulation de conduite [Lucas et al., 2020, Reinhard et al., 2017], tandis que leur utilisation pour la recherche sur les piétons est limitée et plus récente [Schneider and Bengler, 2020]. La recherche sur l'incarnation est également un sujet récurrent de la recherche sur la RV. Les représentations que les individus se font de leur espace environnant dépendent de leurs représentations perceptives et motrices de leur propre corps. Par exemple, la façon dont une personne évalue un objet ou un environnement peut dépendre de la position et des mouvements de son corps virtuel. L'incarnation dans la RV pourrait être définie comme suit : l'incarnation envers un corps est "l'impression qui se produit lorsque les caractéristiques d'un corps virtuel sont assimilées comme s'il s'agissait de ses propres caractéristiques biologiques". [Kilteni et al., 2012a]. Au départ, les VE étaient considérées comme un outil qu'un seul utilisateur pouvait utiliser à la fois. Aujourd'hui, cependant, les VE peuvent être partagés, permettant à différents utilisateurs d'être dans le même VE simultanément, étendant ainsi la RV à un outil multi-utilisateurs. Dans cette optique, les environnements virtuels collaboratifs (CVE) sont un sujet de recherche qui a suscité une forte attention ces dernières années, notamment à la suite de la pandémie de Covid-19 et de la nécessité de travailler à distance grâce aux CVE. Les possibilités des CVE en termes d'utilisation ont été explorées par les chercheurs [Hrimech et al., 2011] qui ont comparé différentes métaphores d'interaction, mettant en évidence la possibilité d'utiliser ces environnements pour le travail collaboratif. La représentation d'avatars, qui fait souvent partie de la recherche sur l'incarnation et les CVE, est confrontée à différents défis, tels que l'acquisition des mouvements et des expressions faciales des utilisateurs, l'animation et le contrôle en temps réel des représentations 3D des utilisateurs, ou encore la fourniture d'un retour sensoriel réaliste à l'utilisateur. La création d'un avatar réaliste et fidèle est une tâche difficile et consommatrice de ressources. En outre, le fait de disposer d'un avatar de haute fidélité peut accroître les attentes de l'utilisateur, qui risque d'être déçu si l'avatar ne réagit pas comme prévu, ce qui entraîne l'effet bien connu de la vallée étrange (uncanny valley). Les utilisateurs peuvent adapter leur comportement en fonction de leurs propres représentations virtuelles et de celles des autres (c'est-à-dire les partenaires de CVE). Plusieurs études ont montré que les utilisateurs ont tendance à se rapprocher et à donner plus d'informations à un avatar attrayant, tandis que le fait d'être en face d'un avatar de grande taille les conduira à accepter facilement des accords injustes (c'est-à-dire à se sentir intimidés).

Nous avons ensuite comparé les différents moyen de navigation.

Table 4.1: Comparaison des moyens de navigations

	Ease to use	Exhausting	Fast travel	Accuracy	Cybersickness
Redirect walking	++	+	- -	++	+
Walk-in-Place	+	+	-	+	++
Stepper machine	+	+++	-	+	++
Point & teleport	- -	- -	+++	+++	-
Flying	-	+	+	-	+++
Gogo-Hand	+	-	++	++	+
World in miniature	+	- -	+	- -	-

Expérience utilisateur et CAVE vs HMD:

Distances écran-œil: La distance œil-écran peut avoir un impact sur la perception de la distance. Les écrans d'un HMD sont plus proches des yeux du spectateur que ceux des CAVE : le regard se concentre donc sur une image située principalement "derrière l'écran", ce qui peut entraîner un conflit vergence-accommodation, la vergence et l'accommodation représentant les deux indices habituels utilisés par notre cerveau pour estimer les distances dans notre vie quotidienne, en particulier les courtes distances [Renner et al., 2013]. Ce conflit bien connu a été signalé comme ayant un impact sur la perception des distances [Ghinea et al., 2018, Marsh et al., 2014]. Dans les systèmes CAVE, cette distance est généralement plus grande et n'est pas constante pendant l'utilisation car les utilisateurs peuvent se déplacer physiquement dans l'espace CAVE. Ainsi, l'accommodation des yeux peut changer continuellement lorsque les utilisateurs s'approchent ou s'éloignent des écrans de la CAVE, ce qui affecte l'estimation de la distance en conséquence. En outre, il a été prouvé que la courbure des lentilles intérieures du HMD induit un effet de barillet dans l'image, ce qui entraîne une minification et, par conséquent, une mauvaise estimation de la distance [Kuhl et al., 2006, 2009]. Cet effet ne se produit généralement pas avec les systèmes CAVE, car la plupart des écrans ne sont pas incurvés. Une étude de 2018 [Ghinea et al., 2018] a essayé de trouver les distances minimales entre lesquelles une distorsion de profondeur utilisant un CAVE ou un HMD peut être vue. Ils ont utilisé l'ajustement de la perception, ils ont constaté que les CAVEs semblent plus précis et adaptés aux courtes distances(deux-trois mètres) que les HMDs, qui seraient donc mieux adaptés aux longues distances. D'autre part, une autre étude, [Naceri et al., 2009], a montré que les systèmes de type CAVE (Wide Stereoscopic Screen Display dans leur étude) étaient plus performants que les HMD pour la perception de la profondeur. [Grechkin et al., 2010] ont comparé l'affichage immersif à grand écran (LSID), le HMD, à la vue réelle à travers le HMD ; ils n'ont trouvé aucune différence significative entre le LSID et le HMD. Cependant, ils ont remarqué une différence significative dans l'estimation de la distance pour la vue en condition réelle à travers le HMD.

Bords d'écran: Il convient de noter qu'avec les systèmes CAVE, même si les écrans et l'affichage des images sont parfaitement bien réglés, les utilisateurs pourront remarquer les bords des écrans et le système de suivi, ce qui pourrait entraîner des effets indésirables lors de l'utilisation des CAVE, comme une perte d'immersion et de présence. Pour les recherches axées sur l'estimation de la distance, cela pourrait influencer et fausser les résultats en raison de la présence des bords. Les participants peuvent inconsciemment ou consciemment les utiliser comme indices de mesure ; ce problème n'existe pas avec les HMD, ce qui rend certaines expériences discutables si l'on veut rechercher l'impact de facteurs spécifiques tels que la texture du sol ou la couleur des objets sur la perception de la distance. De plus, en utilisant une CAVE, la distance à laquelle l'objet se trouve par rapport au participant peut induire trois paramètres visuels différents [Marsh et al., 2014] comme illustré dans Figure 1.12.

FOV: Le champ de vision (FOV) change avec l'écran. Le FOV est défini par l'étendue de ce que l'utilisateur peut voir avec ses yeux, généralement exprimée en degrés. Le FOV horizontal naturel de l'être humain est d'environ 200°, tandis qu'en réalité virtuelle, le FOV est limité par la taille de l'écran : les HMD offrent généralement un FOV d'environ 100° (les HMD récents peuvent toutefois proposer un FOV plus large), tandis que les systèmes CAVE offrent un FOV beaucoup plus large [Mallaro et al., 2017]. Des travaux antérieurs comparant les HMD et les CAVE ont démontré que ce facteur peut affecter les estimations de distance [Knapp and Loomis, 2004, Messing and Durgin, 2005, Renner et al., 2013].

FOR: Le champ de vision (FOR), différent du champ de vue et non lié à celui-ci, est une autre différence notable entre les HMD et les CAVE. Le champ visuel est la zone visible qui peut être évaluée lorsque l'on bouge la tête. Le FOR est plus large dans les HMD que dans les CAVE (voir Figure 2.3). En effet, dans un système CAVE typique (par exemple, un CAVE à 4 côtés de 3 mètres de côté), si l'utilisateur fait face à l'écran frontal en se tenant près de lui et qu'il ne bouge pas la tête mais seulement les yeux, il ne peut pas voir les limites du système, et donc, ne pas quitter l'environnement virtuel, alors qu'avec les HMD, s'il lève les yeux, il pourra voir les bords des écrans. En revanche, dans les systèmes CAVE, si un participant regarde autour de lui (par exemple, derrière lui), il risque de voir en dehors du monde virtuel car il n'y a peut-être pas d'écran physique, alors qu'avec les HMD, il peut regarder tout autour sans quitter l'environnement virtuel.

Éléments concrets : En raison des progrès technologiques et de l'accessibilité, il existe une différence entre les paramètres graphiques des HMD et des CAVE. En effet, les CAVE sont généralement supportés par des ordinateurs puissants et souvent à la pointe de la technologie (du moins au moment de leur construction), tandis que les HMD sont construits pour répondre à un marché grand public. Une CAVE est plus chère, plus difficile à installer et plus encombrante que les HMD, une technologie relativement bon marché (par exemple, environ 300 € pour le modèle le moins cher), et de plus, aujourd'hui, même les smartphones peuvent exécuter des applications de RV. Il est donc moins courant de disposer de CAVE pour la recherche et les cas d'utilisation réels sont moins fréquents, ce qui explique que certaines études qui avaient initialement l'intention d'utiliser la technologie CAVE se révèlent être des HMD. Les CAVE ne sont pas une solution adaptée en raison de leur prix et de leur taille : en raison de la difficulté à les déplacer, ils obligent généralement les utilisateurs finaux à se rendre sur le lieu physique où se trouve le matériel. Par conséquent, la diffusion de cette solution sur tous les sites industriels est irréalisable. De plus, le clavier et la souris sont compliqués à apprendre pour les débutants, alors que l'utilisation d'un système de suivi offre une interaction plus accessible et plus naturelle pour les utilisateurs. Cependant, ce dernier est une technologie moins stable en raison de sa relative nouveauté, certains problèmes de suivi peuvent être rencontrés, en outre, il nécessite plus de préparation pour le faire fonctionner. Les dispositifs à porter constituent également une différence majeure entre les CAVE et les HMD ; en effet, les premiers obligent l'utilisateur à porter des lunettes sans fil légères, tandis que les seconds obligent le participant à porter un dispositif relativement lourd sur la tête, qui est parfois également relié à l'ordinateur par un câble, ce qui limite les mouvements et la liberté de mouvement. En ce qui concerne l'interaction, les deux dispositifs utilisent des contrôleurs sans fil pour interagir dans la réalité virtuelle, mais dans un système, l'utilisateur voit les contrôleurs alors que dans l'autre, les contrôleurs doivent être rendus par la réalité virtuelle.

Les technologies de RV progressant rapidement, l'estimation de la distance avec les HMD récents semble s'améliorer [Kelly et al., 2017], ce qui peut provenir d'une amélioration de la qualité de l'image, du FOV, de la miniaturisation, de la profondeur de champ ou du système de suivi. Ces problèmes techniques peuvent disparaître avec le progrès technologique [Kelly et al., 2017, Renner et al., 2013, Cordeil et al., 2017], améliorant ainsi tous les aspects de l'expérience utilisateur, y compris le cybersickness, la perception de la distance ou la fatigue oculaire. Ces améliorations sont cependant moins observées avec les systèmes CAVE, car ils ont tendance à se répandre dans les laboratoires de recherche ou les grandes entreprises, et leur prix reste élevé, ce qui les rend difficilement disponibles pour un usage personnel ou presque impossible.

Approche expérimentale et expérimentations:

Le sujet de cette thèse est : "L'expérience de l'utilisateur en immersion virtuelle : une étude des facteurs d'échelle pour une perception similaire dans un CAVE et un HMD". Sur la base de cet énoncé, nous avons d'abord examiné l'évolution des dispositifs de RV et présenté les caractéristiques des dispositifs les plus populaires aujourd'hui. Par la suite, nous avons cherché à caractériser l'expérience de l'utilisateur et les différentes caractéristiques des dispositifs qui pourraient l'influencer. Nous avons exploré en profondeur deux dispositifs particuliers : les systèmes CAVE et les casques de RV. Nous avons constaté que divers domaines de recherche utilisent l'un ou l'autre sans donner de raison particulière, d'avantage ou de préférence. Compte tenu de cette absence de comparaison objective, nous nous sommes demandé si un CAVE et un casque de visualisation offraient des expériences différentes aux utilisateurs. Cela nous a conduit à définir deux questions de recherche plus précises qui nous permettraient de commencer à répondre :

- **Quelles sont les caractéristiques du dispositif qui pourraient affecter l'expérience des utilisateurs lors de l'exécution d'une tâche particulière (par exemple, la navigation ou la manipulation) ?**
- **Il est possible d'avoir une expérience utilisateur similaire avec ces deux technologies?**

Pour répondre à ces grandes questions de recherche, nous avons sélectionné des points plus spécifiques, nous permettant de comparer les deux dispositifs en limitant au maximum les biais pouvant provenir d'autres facteurs. En ce sens, pour nos études expérimentales, nous avons choisi de nous concentrer sur certaines des dissemblances mentionnées ci-dessus. Nous les avons choisies car il s'agit de différences inhérentes aux technologies, qui ne seront pas résolues par les développements technologiques des prochaines années. Nous avons également sélectionné des facteurs spécifiques qui pourraient influencer l'expérience de l'utilisateur selon notre analyse documentaire.

Par conséquent, nous avons formulé les hypothèses de travail suivantes :

- **Le poids du dispositif porté, casque pour HMD ou lunettes pour CAVE, aurait un impact sur**

la distance perçue parcourue.

- **La distance de l'écran, différente entre le HMD et le CAVE, aurait des résultats différents sur l'estimation de la distance pendant l'interaction à courte distance.**
- **La FOR, plus large dans le HMD, favoriserait cet affichage pour les tâches de navigation en réduisant le temps nécessaire à la réalisation de la tâche, la nécessité d'effectuer des rotations de la tête et en augmentant les retours positifs des utilisateurs.**
- **La visualisation du corps dans les CAVE ne permettrait pas de surmonter le flux optique plus élevé par rapport aux HMD, ce qui entraînerait un niveau de cybersickness plus élevé dans les premiers (c'est-à-dire les systèmes CAVE).**

La différence dans le matériel porté par les utilisateurs existera toujours entre les CAVE et les HMD (c'est-à-dire les lunettes par rapport aux casques). En effet, à moins d'une évolution surprenante, les casques de réalité immersive ne pèseront pas moins de cent grammes, et comme indiqué précédemment, le poids porté peut influencer la distance perçue. Deuxièmement, la distance œil-écran est différente entre nos deux systèmes. Pour les CAVE, cette distance est plus grande et non fixe, alors que pour les HMD, elle est plus courte et fixe. En fait, cette distance peut avoir un effet sur la perception, en influençant l'estimation de la distance. Le FOV et le FOR dépendent du dispositif. Tous les HMD offrent une FOR de 360°, tandis que les CAVE ne fournissent généralement pas une FOR complète (les CAVE à six faces sont rares). Les deux dispositifs offrent un FOV limité. Ces limitations et différences peuvent avoir un impact sur le comportement des utilisateurs pour les tâches spécifiques, en particulier lorsqu'elles nécessitent de regarder autour de soi. Enfin, tous les facteurs précédents peuvent avoir un impact sur le cybersickness. Il est donc important de mener des expériences pour mettre en évidence la façon dont les différences entre les appareils peuvent avoir un impact sur le cyber-malaise ressenti par les participants.

Conclusion:

Le comportement des utilisateurs et la façon dont ils vivent la réalité virtuelle ne sont pas encore vraiment compris, et nous sommes confrontés à une quantité croissante de types d'écrans permettant aux gens d'entrer dans un environnement virtuel. Les avantages et les inconvénients de ces dispositifs ne sont donc pas déterminés, et nous pouvons légitimement nous demander pourquoi utiliser un dispositif plutôt qu'un autre. Les différences qui définissent ces dispositifs d'affichage peuvent avoir un impact sur le comportement et l'expérience de l'utilisateur, en influençant sa visualisation de l'environnement virtuel, son comportement d'interaction ou de navigation. Pour répondre à ces questions, nous avons mené quatre expériences pour comparer deux dispositifs spécifiques, les CAVE et les HMD.

Une expérience a été réalisée pour chaque point extrait en tant que différences fondamentales : l'une a cherché les différences de poids du dispositif porté. Les résultats montrent que la distance est surestimée au-delà de trois mètres, et que le poids du HMD lui-même peut avoir un impact sur la distance parcourue. Cependant, à lui seul, ce facteur n'explique pas la sous-estimation constatée dans les études. Il se peut que cette différence de dispositif ne soit pas prise en compte comme ayant un impact sur l'expérience de l'utilisateur pour les distances inférieures à trois mètres. Une deuxième étude a exploré la différence entre le champ de vision (FOV) et le champ d'observation (FOR). De manière surprenante, aucune différence significative entre les deux dispositifs n'a été trouvée pour les angles de rotation, la fréquence cardiaque et le cybersickness. Cependant, le temps de réalisation de la tâche était plus court avec le dispositif CAVE, et les commentaires des participants étaient en faveur de l'utilisation des HMD. Par conséquent, pour une application nécessitant des rotations régulières du point de vue, les HMD sont à privilégier. Une troisième expérience a porté sur la différence entre les distances œil-écran. Les résultats ne montrent aucune différence significative entre les deux dispositifs. Cependant, une surestimation a été observée pour la distance de 15 cm, confirmant la difficulté de percevoir correctement les courtes distances à travers les outils de réalité virtuelle. Une dernière étude a porté sur le cybersickness ; ce facteur est un domaine bien documenté avec les dispositifs HMD mais pas autant avec les CAVE.

Nos questions de recherche et l'objectif de ce travail étaient de comparer deux affichages de réalité virtuelle différents à travers l'expérience utilisateur. À cet égard, nos principales questions étaient les suivantes :

- **Quelles sont les caractéristiques du dispositif qui pourraient affecter l'expérience des utilisateurs lors de l'exécution d'une tâche particulière (par exemple, la navigation ou la manipulation) ?**
- **Il est possible d'avoir une expérience utilisateur similaire avec ces deux technologies?**

En d'autres termes, quelles sont les caractéristiques des appareils qui affectent l'expérience utilisateur et ont un impact sur celle-ci ? et cette différence peut-elle être surmontée par l'application ou la pratique ? Les expériences développées sont toutes axées sur un aspect spécifique différenciant les CAVE et les HMD, pour lequel des études antérieures ont montré qu'il pouvait avoir un impact sur l'UX, tout en limitant tout biais pouvant provenir d'un autre facteur.

Les contributions significatives de ce travail se résument comme suit :

Comparaison des CAVE et des HMD : Dans notre revue, nous avons trouvé peu d'articles qui comparaient les CAVEs et les HMDs, ou qui donnaient une analyse détaillée de ces deux dispositifs. Ce travail peut aider les chercheurs qui souhaitent étudier ce sujet à avoir un aperçu des différentes limites des deux technologies, de leurs points communs et divergents. Nous fournissons ainsi une base de recherche intéressante pour traiter le sujet.

Marche avec des dispositifs de RV : Nous avons mené une expérience sur la perception des distances de marche. Nos résultats montrent que pour un déplacement physique de moins de trois mètres, il n'y a pas de différence significative entre les HMD et les CAVE. Du moins, cette distance ne sera pas induite par le poids du casque immersif. Il est important de noter que la plupart des configurations utilisées pour les applications de réalité virtuelle, qu'il s'agisse de l'espace réservé par les utilisateurs de HMD ou de la taille des CAVE courants, dépassent rarement neuf mètres carrés. Ce résultat, bien qu'il ne soit pas applicable à tous les cas d'utilisation, peut être utilisé dans une grande majorité des cas d'utilisation.

Navigation dans les VE : Alors que nous nous attendions à voir des différences de comportement pour une tâche de navigation dans un environnement de grande taille, et qui plus est, avec une tâche nécessitant que l'utilisateur tourne beaucoup pour regarder autour de lui, nous avons été surpris de constater qu'il n'y avait pas de différence significative entre les deux appareils, même si l'un d'eux semblait mieux adapté à ce type d'application. Nous avons seulement noté une différence dans le temps nécessaire à la réalisation de la tâche. Le CAVE nécessite donc plus de temps pour réaliser la même tâche. De plus, les participants ont objectivement préféré l'utilisation du casque immersif. Sans différence significative en termes de rotation ou de cybersickness, mais avec un temps plus court et une préférence de l'utilisateur pour les HMD, il serait plus intéressant d'utiliser ces derniers pour des applications d'exploration de grands environnements.

Distance égocentrique: Là encore, nous n'avons pas trouvé de différence significative entre nos deux dispositifs. Il est cependant à noter que la perception des courtes distances est compliquée à reproduire (dans notre cas si la distance est inférieure à 15 cm, une différence significative apparaît dans nos deux conditions). Nous limitons nos résultats à une perception de la distance pour des objets relativement petits, un déplacement entre 15 et 80 cm et une distance inférieure à 1m.

Il est intéressant de constater que nous n'avons pas pu mettre en évidence de différences significatives entre nos deux dispositifs, malgré les expériences qui visaient à mettre en évidence les différences qui apparaîtraient du fait des différences techniques entre nos deux outils de réalité virtuelle. De plus, ces différences auraient dû avoir un rôle significatif sur l'expérience utilisateur selon l'étude précédente.

Limitations

Nos différentes expériences ont plusieurs limites.

Tout d'abord, elles sont toutes limitées à des cas d'utilisation stricts. Nous ne pouvons pas généraliser nos résultats. Elles ont toutes été menées en période de pandémie, donc avec un port de masque obligatoire, ce qui a pu avoir un impact sur certaines mesures. En raison de certains problèmes techniques, du côté du développement des applications mais aussi de la disponibilité du matériel, nous avons dû utiliser deux CAVE différents, et certaines applications auraient pu être améliorées visuellement.

La limitation la plus importante provient de notre décision initiale d'isoler nos facteurs. En essayant d'isoler nos paramètres pour voir s'ils avaient un impact sur l'expérience utilisateur indépendamment du reste, nous n'avons pas pris en compte le fait que même s'ils ne modifiaient pas indépendamment l'expérience utilisateur, l'accumulation de différents facteurs pouvait avoir un impact. Ainsi, le protocole et le développement de notre application auraient fait en sorte qu'il n'y ait pas de différence significative.

Perspectives

Les différentes contributions présentées constituent la première étape d'une caractérisation de l'utilisabilité des dispositifs CAVE et HMD. Ainsi, nous présentons ci-après, ce qui pourrait être abordé ultérieurement afin de compléter cette caractérisation.

Nous souhaitons continuer à comparer les deux dispositifs, en isolant d'autres facteurs pour voir si l'un d'entre eux est un facteur déterminant dans l'expérience utilisateur et s'il rend un dispositif clairement plus adapté à certains usages. Ainsi, nous conseillerions d'abord de concentrer les recherches ultérieures sur les points spécifiques que nous n'avons pas abordés, comme la visualisation du corps, la luminosité de l'image, la visualisation des bords de l'écran ou les limites de résolution (qui sont apparus relativement souvent dans nos études, lors de l'utilisation des HMD).

Comme nos études n'ont été menées qu'avec quelques participants (une vingtaine à chaque fois), une validation avec un plus grand nombre pourrait être nécessaire, notamment pour les résultats inattendus, comme le comportement de l'utilisateur lors d'une tâche de navigation dans les deux dispositifs. De plus, les CAVE sont principalement considérés comme des dispositifs permettant une collaboration plus efficace ou des revues de projets. La réalisation d'une étude claire sur cette comparaison pourrait être intéressante.

Au vu de nos résultats, il serait intéressant dans un second temps de voir l'impact de plusieurs facteurs. Peut-être que certains facteurs, mis ensemble, permettront de mettre en avant des différences qui, additionnées, pourront influencer l'expérience utilisateur.

Enfin, avec la multitude de HMD et de systèmes CAVE, et leur évolution rapide, les études sur les caractéristiques qui évolueront le plus vite et leur impact sur l'expérience utilisateur devraient être privilégiées (par exemple, la résolution de l'écran est plus susceptible de changer que la visualisation des bords de l'écran).

Prénom NOM

titre

Résumé : Cette thèse explore l'expérience utilisateur en immersion virtuelle, en comparant les différences entre les CAVE (CAVE Automatic Virtual Environment) et les casques de réalité immersive (HMD). Cette recherche a été menées dans le cadre d'une cotutelle entre deux laboratoires de recherche en France (LISPEN) et en Allemagne (IMI). Quatre expériences ont été conçues pour se concentrer sur les différences fondamentales entre les deux dispositifs, notamment le poids, la distance œil-écran, le champ de vision et le champ d'observation, et le mal de simulateur. Les résultats montrent qu'il n'y a pas de différence significative dans la distance de marche perçue entre les deux dispositifs jusqu'à 3 mètres, et les utilisateurs préfèrent les casques en termes d'expérience et de temps de complétion. Nos résultats fournissent des lignes directrices pour déterminer quel dispositif est le plus adapté pour les applications spécifiques en fonction des facteurs tels que la navigation, l'interaction et l'expérience utilisateur..

Mots clés : Expérience utilisateur, réalité virtuelle, Mal du simulateur, CAVE, HMD

Abstract : This thesis explores user experience in virtual immersion, comparing the differences between CAVE (CAVE Automatic Virtual Environment) and Head-Mounted Displays (HMD). This research was conducted under a cotutelle between two research laboratories in France (LISPEN) and Germany (IMI). Four experiments were designed to focus on the fundamental differences between the two devices, including weight, eye-screen distance, field of view and field of regard, and cybersickness. Results show no significant difference in perceived walk distance between the two devices up to 3 meters, and users prefer HMDs in terms of experience and time completion. Our results provide guidelines for determining which device is most suitable for specific applications based on factors such as navigation, interaction, and user experience.

Keywords : User experience, Virtual reality, Cyber-sickness, CAVE, HMD