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KAVE - Kinect Cave
Design, tools and comparative analysis
with other VR technologies

MASTER DISSERTATION

José Diogo Camacho Freitas
MASTER IN COMPUTER ENGINEERING



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Abstract

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Virtual reality has been delivered through many different forms and iterations. One of them is the CAVE. CAVE systems have developed over the years but they are still have prohibitive costs and are rather complex to implement. In this thesis we propose our own low-cost CAVE system - comprised of details about the setup as well as a calibration software that was developed to help achieve the goals of this thesis - and compare it to other lost-cost CAVEs found in the literature. This thesis also encompasses a presence study that was performed as a result of assessing the resulting CAVE. This study compared CAVE, PC and Head-Mounted Display in terms of presence and workload through the use of validated questionnaires found in the literature. The resulting data showed HMD induced higher sense of presence than the CAVE, and CAVE induced higher sense of presence than the PC. Regarding workload of the system, the data also showed no statistically meaningful differences between the three technologies except for the physical demand of performing a task in a CAVE compared to performing the same task in the PC.

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List of Abbreviations

HMD	Head Mounted Display
CAVE	Cave Automatic Virtual Environment
VW	Virtual World
VE	Virtual Environment
FOV	Field Of View
POV	Point Of View

Chapter 1

Introduction

Virtual reality has developed a lot over the years and important work has laid the foundation for the promise that virtual reality set out to achieve - to transport users to lush worlds and environments in which users can freely interact and feel as if they were actually there. Everybody has seen those movies where people put a device with a lot of wires on their heads and lay down on a bed and get transported to a virtual world, ready to interact and explore at the users heart content, like a dream taking form. While the advances on technology have not quite reached this point, in an ever-increasing generation converted to technologies, virtual reality has taken shape through various focus, to help humans in some way.

What started out as complex and expensive technology with a big promise, with the increase of interest in the area, efforts have been made to lower the entry point, setup complexion and production costs.

Virtual reality nowadays come in different technologies - through our smartphones, Head Mounted Displays or embodiments of virtual spaces like CAVEs. While CAVE solution haven't quite matured yet as Head Mounted Displays, it is currently an enthusiastic solution with lot of potential (see [here](#)) since it represents a paradigm shift in Virtual Reality compared to Head Mounted Displays.

However, since CAVE systems are not as matured, the costs and complexity are higher compared to other technologies and most CAVEs use wearable technology that helps in tracking the user body or are only specialized in a very small field. With that said, there is an opportunity here to push the cost and complexity of CAVEs down as well as present another way of setting up a multi purpose CAVE that doesn't rely on conventional ways, such as not using tracking technology that does not use cumbersome wearable technology.

1.1 Objectives

The output of this thesis will be the implementation of a low-cost CAVE at M-ITI (Madeira Interactive Technologies Institute), a calibration software up to four surfaces which will be used to calibrate the implemented Cave. However, this software is a general tool and works for any four wall configuration. Also this thesis should encompass a study which evaluates the implemented Cave and compares it to a computer monitor and an Head-mounted Display in terms of presence and system workload. The knowledge derived from this study should add up to other presence studies found in the literature.

1.2 Document structure

In chapter 2, we thoroughly review the literature, the work that has been done in virtual reality, the parameters to assess and evaluate it. In chapter 3 we propose our solution and dwell in detail about the rationale behind the decisions related to physical and software setup as well as discuss the importance of each solution component. In chapter 4, we describe the study that was conducted to assess and validate our solution as well as the results of this study. In chapter 5 we discuss the results of study and compare it with the literature. Finally, in chapter refconclusions we wrap it all by doing a post-mortem on the project, its objectives and generated knowledge.

Chapter 2

Related Work

2.1 Emergence of VR

To trace the beginning of virtual reality we need to go back to the 60's with the introduction of the Sensorama (Figure 2.1) - a machine that delivered a multi-sensory virtual experience. It was actually non-interactive, with the user being a spectator in a sensory storytelling event augmented crudely in four of the five human senses - sight, hearing, smell, touch - leaving out taste.



FIGURE 2.1: The Sensorama - regarded as the first machine related to Virtual reality

In 1968, Ian Sutherland developed what is considered the first Head Mounted Display (HMD) virtual reality system called the Sword of Damocles. It tracked

the position of the eyes and head of the user and refreshed its image according to the user's position. This was a major breakthrough because, as we will see throughout this chapter, the idea of tracking the eyes and head position is present in most modern virtual reality technologies.

Other novel virtual reality technologies were developed over the years but never actually caught up.

Around the 80's, interest arose regarding gloves that could track the user's hand, measuring joint angles and pressure, to interact with a virtual world. Such cases are the Sayre gloves, developed in 1977, by Daniel Sandin and Tom DeFanti. Successive development caught on with Dataglove, worked on by Thomas G. Zimmerman but it wasn't until the introduction of the Power Glove that efforts were made to actually have a VR glove directed to consumers, which was made for the Nintendo Entertainment Systems but it proved to be a commercial failure.

Through the years, attention turned once again to Head Mounted Display and physical spaces emulating virtual world or a combination of both. Such examples are found in VCASS - a flight simulator developed US Air Force's Armstrong Medial Research laboratories in 1982 in which the pilot wore an HMD that expanded the control of the cockpit by providing information about optimal flight path. Another example is the BOOM, developed in 1989 by Fake Space Labs. BOOM (Figure 2.2) is another take on Head Mounted Displays by having a mechanical arm with the end of the arm containing two monitors (one for each eye). The user moves the mechanical arm while looking through the eyes' monitor and thus, navigates through the virtual world with the mechanical arm tracking the position and orientation of the box containing the eyes' monitors. A classic application of virtual reality is the Wind Tunnel and was applied through Virtual Wind Tunnel - developed in the early 90s at NASA to further investigation in the flow of wind through objects and their aerodynamics. This Virtual Wind Tunnel was also used in conjunction with BOOM and DataGlove, which was deemed a failure on its own but in conjunction with other technologies, rose in prominence and found its place among virtual reality technologies. We'll further cover HMD in section 2.4.

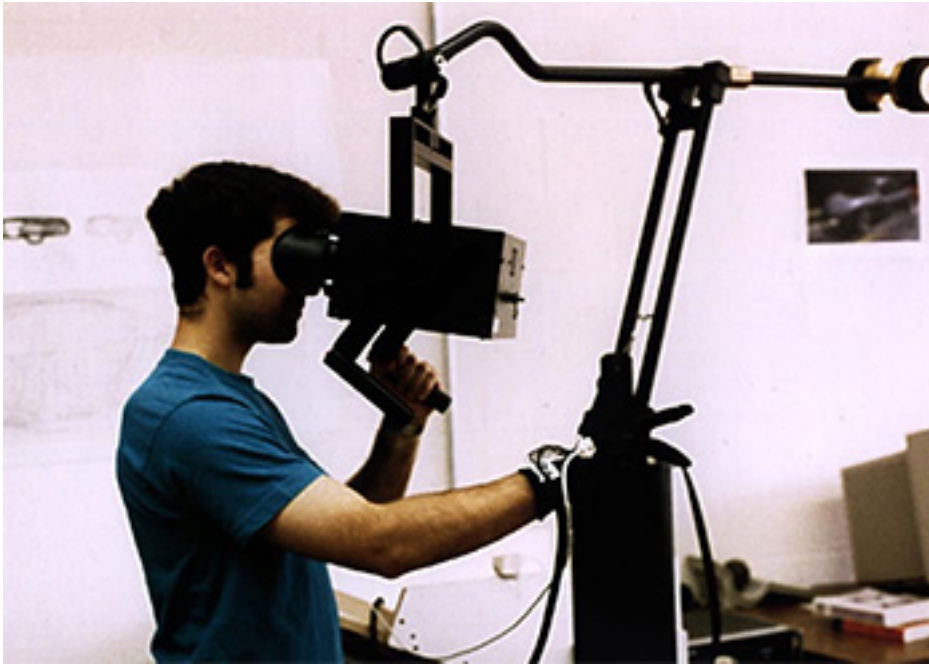


FIGURE 2.2: BOOM is regarded as the first precursor to modern Head-Mounted Displays

In 1992, University of Illinois presented the CAVE (CAVE Automatic Virtual Environment), with the purpose of scientific data visualization. This marked an important breakthrough in virtual reality as we will see thoroughly explored in section 2.5.

2.2 Virtual Reality Applications

Let's discuss why VR has been a buzz word in recent years and what is the motivation to develop this type of technologies as well as its applications in current technological venues.

2.2.1 Motivation

Compared to human-machine interaction paradigms that we grew up on, for example keyboard and mouse, Virtual Reality opens up new venues in human-computer interaction in a more natural and realistic way. In this context, the word natural refers to the fact that the user often does not have to learn complicated interfaces to watch and manipulate the environment. Let's give an example - While playing a first-person shooter game with mouse and keyboard, to "look" around the environment we drag the mouse to change

the image displaying on the screen. In other words, we use our hands to perform a task that naturally we use our head to accomplish. Virtual Reality changes this by introducing tracking in which the tracked person moves their head and a sensor picks up his head's position and orientation while changing and updating the displayed image to match this. Therefore many applications like real-life simulators or data visualization systems were developed relatively quickly. Across the years VR has been applied in a number of fields.

2.2.2 Education

The first instances of applications of VR in education were reported in late 1950 [1], where a precursor to VR was used extensively in flight simulators to train pilots (Figure 2.3) and astronauts. These application would be improved and built upon in research institutes for military purpose. Currently, many civil companies use VR for education and training because of lower operating costs and safety compared to real life simulators. Another application of VR was proposed consisting of the usage of VR to train medics in difficult operations such as endosurgery, eye operations and leg operations.



FIGURE 2.3: An aircraft pilot in a VR simulation to enhance his piloting skills

2.2.3 Data Visualization

People have been gathering large amounts of data for a long time but presenting this enormous amount of information in a way that is easily digested

for humans is difficult. Desktop computers with simpler interactions always have been far from being optimal for data presentation, digestion and manipulation. The natural way of interacting with machines promised by Virtual Reality is an improvement.

2.2.4 Product pipeline

With ever greater market competition, the manufacturing industry steered towards to "rapid response of market"[2]. One of the most desirable outcomes to accomplish this rapid response in product pipeline is the ability to visualize the final product being developed in the highest fidelity possible. Virtual Reality was early on adopted to accomplish this enabling for example engineers or interior designers to visualize their ideas before actually starting development. Virtual Reality not only allows visualization but also tweaks and changes to the product in real-time. For example, an interior designer can visualize its sketches in 3D and change colors, textures or position of objects in real-time, severely cutting costs and saving time. All in all, applying virtual reality to product pipeline enables a 3-dimensional, visible and interactive environment for conceptualization, design and manufacturing.

2.2.5 Telepresence

Telepresence[3] refers to the action of people operating in remote environments (different from their own) by the use of Virtual Reality. This became a popular approach when the environment prove to be hazardous to human life and a machine is the best alternative to carry out the "operation". While the goal is to have autonomous robots equipped with artificial intelligence (which could operate in said hazardous environments), a person supervising its behavior is still required in most cases and here we find a space to apply Virtual Reality.

2.2.6 Entertainment

Perhaps, entertainment is the most recognized application of Virtual Reality in recent years. This is due to the fact that Virtual Reality has constantly been getting cheaper and cheaper and the hardware to support it more powerful, providing accessibility to the masses of a technology that previously was mainly used for research and realistic simulation. Getting this type of technology to the masses generated a market where companies thrive to

release Virtual Reality games like SEGA, Nintendo or Valve (through their Steam store). What initially was a market directed to PC users, these companies started to push also Virtual Reality in mobile phones. Apart from this market of integrating Virtual Reality in games and sell them, cinema companies also have used Virtual Reality, for example for transferring emotion and expression from a real-life actor's face to the face of cartoon characters.

2.3 Immersion and Presence

Across all VR technologies, *immersion* of Virtual Reality systems has been a much researched topic. Associated and used interchangeably with the term *presence*, they are not the same.

2.3.1 Immersion

Mel Slater[4] demonstrates the above by explaining that immersion is defined by how much the system's visual and tracking components approximates the sensory feel of their real-world counterparts, namely what our eyes see and how our bodies move. In other words, Mel Slater argues that, between two VR systems, one is more immersible than the other by how well they preserve the stimuli that we experience through our eyes and body.

But what our eyes see and our perception of the world is subjective, as each individual sees the world differently. This does not defer us to assess immersion in a VR system objectively. Mel Slater adds that this ambiguity is similar to the perception of colors. People may have a different perception of the tone of a particular color[5], but we still can objectively assess the color by its wavelength distribution. Infinitesimal small changes in wavelength are different colors[6], yet no one can perceive it as such. Mel Slater here introduces the distinction of immersion and presence by saying that if immersion is the objectively and measurable wavelength of color, then presence is the human perception of color.

This is interesting because even if, between two VR systems, one objectively preserves the same real world stimuli of our eyes and body when put against the other, it can still have perceptual impacts in different people in terms of presence.

While Mel Slater says that immersion refers to the actual amount of sensory fidelity a VR system delivers, Daniel Mestre [7] explains with a different point of view, but with many overlaps with Mel Slater views. For Daniel immersion is achieved by removing as much real-world sensory feel as possible and replace these with the corresponding component in the VR system responsible for emulating the real world sensation. So, a VR system, in terms of immersion, is an emulation of the human body through a machine, that curiously appeared as a way to break the limitations of humans.

Since immersion is measurable and controllable, Bowman[8] proposes in his paper a list of components that affect overall system immersion and includes:

- **Field of View** The space perceived by the user at a given instant.
- **Field of regard** The total space surrounding the user, in which he can interact.
- **Display Resolution** A measure that takes into account the number of pixels in vertical and horizontal axis of a display.
- **Stereoscopy** An additional depth cue that uses different images to each eye.
- **Head-based Rendering** The tracking equipment calculates the physical position and orientation of the user's head and outputs a corresponding and adaptive display.
- **Frame rate** The amount of image frames the system outputs, in average, per second.
- **Refresh rate** The number of times in a second the technology updates its image buffer and "refreshes" the image.

2.3.2 Types of immersion systems

As mentioned above, a computer generates sensory data that is delivered to human senses and this is called immersion. The quality of this sensory data determines the level of immersion of the system. In theory, to achieve the highest quality of immersion, the virtual reality system should permeate all of the user senses and the virtual environment react realistically to the users' action. But alas, in practice the situation is very different. Most applications simulate one or two of the users' senses, often with blurry displays

and laggy (delayed, stuttering) movements. According to [9], VR systems can be group according to their level of immersion:

- **Desktop VR** This is the simplest form of VR applications. It uses a single monitor (i.e a PC screen of a smartphone) as the display of the VR system. As most monitors, the image produced is monoscopic in nature. Tracking of the user isn't performed and the level of sensory fidelity is low.
- **Fish Tank VR** This type of virtual reality application takes the Desktop VR as a base and adds head tracking to it. Head tracking generates motion parallax effect and this contributes greatly to the feeling of "being there" inside the virtual environment. These type of applications often feature some type of shutter glasses that users wear to produce a stereoscopic display.
- **Immersive systems** This type of systems is what we currently associate with virtual reality where the user is put completely immersed inside a virtual environment, often with Head Mounted Displays to track users head position and orientation as well as delivering the user stereoscopic display. Caves also belong to this category.

2.3.3 Presence

Presence is an important concept and it is not only portrayed in Virtual Reality. In fact, researchers have studied presence in various fields such as computer science, business, education, medicine, entertainment, artificial intelligence, philosophy and many more. [10]

Presence can assume a different number of personas. In the literature, six main presence roles have been identified[11] but we will just focus on four of them to lead to the concept of presence in Virtual Reality. The four are the following:[12]

Presence as social richness Mainly portrayed in communication in organizations, presence here refers to the extent to which a person is perceived by others as sociable, warm, sensitive, or intimate when engaging in interaction with other people. The concepts of social presence theory[13] and organizational tasks[14] were developed to find a better fit between communication

media and organizational tasks to produce maximum efficiency and satisfaction.

Presence as realism This conceptualization of presence is regarding to the extent of a said medium can produce accurate representations of real world objects, events or people. Typically this conceptualization of presence appears assessing consumer's response to variations in the characteristics of a medium. However, Lombard[11] here states that this conceptualization fails to separate two different types of realism: Social realism and perceptual realism. Social realism refers to the way the medium's content is bound by what really happens in the real world. For example, let's imagine an action science fiction movie depicting space warfare between two opposing factions. Here, the social realism is low - because there are no battles in space using spaceships yet - but the perceptual realism may be high, as in, the people and events portrayed could behave like one should expect if they did, in fact, exist.

Presence as immersion Here, presence relates to the idea of perceptual and psychological immersion. This perceptual immersion relates to the effort of the medium to submerge the perceptual system of the user and can be objectively measured by the amount of user's senses covered by said medium [15]. Psychological immersion occurs when the users feels engaged, absorbed and engrossed with the system.

Presence as transportation This conceptualization of presence has taken three different forms through various authors. The first is about the premise of transporting the user to the medium. It is especially important in Virtual reality, where many virtual reality applications try to transport the user to said virtual environment [4], [15], [16]. The ability to interact with a remote environment is defined as telepresence[3] or teleoperation[17] and is important terminology in the dynamics of transporting user to virtual environments. Virtual environments may be mistakenly associated only with environments composed of 3D graphics but this type of "You are There" presence is also encountered in Virtual Tours[18] at museums or computer software like Google EarthVR ¹.

We've seen the transportation of the user to the medium's environment but what about bringing the medium's environment to the user? That is

¹<https://vr.google.com/earth/>

the intrinsic idea of "It is here" defined by Lombard [11]. This also invokes a sense of presence as transportation and is mainly applied in Augmented Reality[19], since there are many overlaps in the concept.

The third idea of presence as transportation is about a shared space environment where more than one user shares the same space and time. For example, collaborative work inside a CAVE application or as simple as a video conference Skype² call. More about this type of shared space presence has been studied in [20].

Presence, according to Mel Slater [4], is the perception, the feeling of being transported and belonging to the virtual world. He gives a particular interesting example of listening to music. A sign of presence, according to Mel Slater, is if a person closes his eyes while listening to opera music on a speaker system and actually feels like he's in a theater with an opera group performing before him. He feels present in the theater. He goes on by adding that if the user eventually loses interest in the music (he doesn't like opera) and states that this behavior has nothing to do with presence. If he likes the music or not, it doesn't deter us from having the feeling of being in an actual theater.

This analogy can be redirected to VR systems. According to Bowman[8], immersion of a VR system depends solely on the system's rendering software and display technologies, as well as its associated sensors, functioning in sync to provide a technological spectrum of immersion. This spectrum, further reinforced in the previous paragraphs, is objective and measurable. A system can have, objectively speaking a higher level of immersion than another. Continuing with Bowman analysis, he says that presence, on the other hand, is different from individual to individual and is context-restrained - depending on the user response. Different users are likely to experience different levels of presence with the same VR systems (in other words, with the same level of immersion defined earlier). Bowman elicit some reasons for changes in presence levels in the same VR systems such as, state of mind of the user and other psychological factors. While the psychology behind what we call presence has gathered a lot of interest in researched in recent years, Bowman adds that we must take a more practical approach of studying the effects of immersion.

²<https://www.skype.com>

2.4 Head Mounted Displays

Head mounted displays, like the name implies, are pieces of hardware mounted on the user's head that incorporate two monitors (typically LCD or OLED) placed in front of the user's eyes. Earlier iterations used CRT (Cathode Ray Tube) monitors but, similarly to what happened with televisions, CRT monitors were substituted by much more modern display technologies.

The images presented in these displays are based on the user's current position and orientation and is measured by a tracking system. This tracking system normally is integrated in the headset itself or in more sophisticated HMDs, the tracker is placed conveniently in a way that these some trackers of the tracking system detect changes in the HMD position and orientation and communicates to the system that the HMD is attached to. Detaching the tracking and visual computation the HMD is required to produce, improves the performance of the HMD.

Since HMD are a piece of technology that is worn by the user there are some design goals it needs to accomplish. It must be lightweight, comfortable and easy to put the HMD on and remove it. In terms of visual fidelity, the LCD should be of the most high fidelity but sometimes, trade offs must be made to favor manufacturing costs and its intended use. Consequently, the prices of HMDs vary a lot - commercial solutions ranging from about 800 dollars to sophisticated military HMD costing millions of dollars.[1]

According to [21], HMDs are separated in two groups - *opaque* and *see-through*. Opaque HMDs totally immersive the user in a computer generated virtual environment and are used in applications that use their own virtual environment in which every asset of the environment is computer generated like 3D architectural visualization of buildings, games and scientific visualization. See-through HMD, on the other hand make use also of computer generated imagery but superimposes these images on top of real world objects, augmenting the real world with computer-generated data. A few examples of nowadays HMD are the Oculus Rift, HTC Vive, which are opaque HMD or Google Glass being see-through. Let's look at at a few characteristics of opaque HMD, namely the Oculus Rift and the HTC Vive.

2.4.1 Oculus Rift

Oculus Rift, as described above, is considered a opaque HMD and was initiated as a Kickstarter campaign in 2012 to fund its development cost. Two models were shipped to people who helped support the development of Oculus Rift through Kickstarter called DK1 and DK2. Let's assume the DK2 (most recent one) to the discussion of Oculus characteristics.

Oculus Rift DK2 features OLED displays, 1080x1200 resolution per eye at a 90Hz refresh rate and a 110° field of view. At the time of the announcement of the Rift, this was one of the highest field of view in market HMDs and one of its marketing flags. Oculus Rift has integrated headphones that provide stereo sound, as well as 3D audio effect (an effect that changes audio source volume based on the users distance to the virtual audio source). The tracking system that Oculus Rift possesses is a 6DOF (Degrees of Freedom) that encompasses an infrared sensor, typically placed at the user's desk that picks up light that is emitted by infrared sensors placed on the HMD, thus enabling positional and rotational tracking of the equipment to be used in Oculus Rift applications. The most common way of using Oculus Rift in applications is by combining the HMD as a visual enhancer and a standard interaction technology like keyboard and mouse or a controller. (See figure 2.4)



FIGURE 2.4: A person using Oculus Rift with an Xbox controller

2.4.2 HTC VIVE

HTC Vive is also an opaque HMD and was developed by HTC and Valve Corporation. It was released in April 2016 and gained tremendous popularity. Similarly to the Oculus Rift, it also features OLED displays in 1080x1200 resolution per eye and the same 110° field of view.

What really distinguished HTC Vive from Oculus Rift is its innovative *room scale* tracking technology and combination of tracked controllers that not only serves as a way to simulate the user's hands but also provide haptic feedback, enabling fluidity in the interaction with the virtual world as well as its menus, if applicable. The headset and controllers have more than 70 infrared sensors that in combination with two stationary infrared-emitting boxes are used to track the user's head, left hand and right hand position and orientation in sub-milimetric precision. Furthermore, this tracking system operates in a maximum space of 4.6 meters by 4.6 meters, which is clearly superior to what the Oculus rift provides. In contrast to Oculus Rift, the HTC VIVE also has a front camera that enables the user to see it's real-world surroundings without the need to remove the headset which is a big advantage in terms of safety of the user.

In figure 2.5 we have an illustration of HTV VIVE and it's main components described above: **A** are the stationary infrared-emitting boxes (called Lightboxes), **B** is the head-mounted itself and **C** represents its controllers.



FIGURE 2.5: Illustration of HTC Vive and its main components

Consolidation - Head Mounted Displays presents itself as a strong contender for technologically pushing Virtual Reality with its immersive displays and fluid interaction methods. In fact, differences between Head-Mounted displays and CAVE systems fuel interesting discussions. These are further explored in section 2.6.

2.5 CAVE

Virtual environments can provide stereoscopic displays and tracking based on the motion of the head that allow users to perceive three-dimensional information, creating a sense of immersion that allows the users senses to be heightened to a level that induces very unique responses in a human-machine relationship. One such system is the CAVE. Very different from HMD approaches, in this section we review what is considered a CAVE, its typical components and take a look at some CAVE systems developed over the years, including low-cost CAVEs like the CAVE proposed in this thesis.

2.5.1 Introduction to CAVEs

CAVE stands for the recursive acronym (CAVE Automatic Virtual Environment) and consists of two or more walls where projectors are conveniently placed to project images in said walls to surround the user in a Virtual Environment - a computer generated artificial environment which a user can sense and interact with - creating an impression of being "inside" the Virtual Environment. Some sort of input device to track the user is also placed in the CAVE to achieve an Immersive VR system previously described. To operate and control this, special software (normally called CAVE software) is required. This software is in charge of controlling the projection of images and video as well overview the interactions the user performs inside CAVE.

A CAVE system is a mixture of physical construction of the CAVE that supports the integration of hardware (sensors) and software and these three elements work in a homogeneous way invisible to the user of CAVE or developer of CAVE applications. The system must be robust enough to exclude as many external dependencies as possible. Like an HMD (i.e HTC VIVE) that you simply have the equipment and load applications in an operating system, the CAVE also must have this robustness of the package (structure,

hardware, software) applied in similar fashion. One of the hindrances that is preventing CAVE to be much more popular is the accessibility and complexity of construction. Nowadays to have a CAVE system running is a complex, expensive and time-costly process. Some companies have found success by commercially building CAVE for the public, like Visbox, providing this package with as less complexity as possible for customers, but similarly to what happens in a lot of products when you mass produce, you lose the flexibility the CAVE can have and sub sequentially limits its potential.

2.5.1.1 First inception of CAVE

In 1993, Carolina Cruz-Neira et al. [22] developed what came to be the first CAVE. Very different from the HMD virtual reality paradigm, it was the first one-to many presentation device presented with off-axis perspective projections including a different way of tracking the user that resulted in less errors and system latency. This large CAVE stands at 9.2 meters in length, 6.1 meters wide by 4 meters tall and was composed of three rear-projection screens (meaning the projectors were delivering the image to the wall from outside the CAVE space designed for interaction) for three walls and a down projection screen for the floor. Projectors used were 1280x512 in resolution at a refresh rate of 120Hz. Audio was delivered from the workstation to multiple speakers placed through the CAVE. Electromagnetic sensors used, produced an electromagnetic field that was captured by the computer in order to determine the user's head and hand position. In order to produce a stereo image (stereo being a depth cue), LCD stereo shutter glasses were used to separate the different images going into the user's eyes. All of this component's information were communicated and synchronized via fiber-optic.

Since the unveiling of the original CAVE, the CAVE design achieved international recognition as the chief of virtual reality technology providing compelling interactions in various fields. Thus, several attempts to build on top of the original CAVE were made to push CAVE-like systems in various fields of virtual reality. The first CAVEs were based on CRT projectors, resulting in blurry and low-contrast images. Fortunately, nowadays with the introduction of crystal-based projectors (DLP), images in a CAVE system have improved significantly compared to CRT ones and, as we will see, image quality has great influence in the immersion of a CAVE.

Now that we've looked at what is a CAVE and how it was introduced, let's further dissect what composes a CAVE and its various components in the next subsection.

2.5.2 CAVE system overview

In this subsection we discuss the CAVE system in terms of its **structure** and **components**. The relationship of these two arguments is especially important because the structure must accommodate the CAVE components in the best way possible. High-performing components, if supported by a poorly designed structure, may bottleneck the components performance and usability.

2.5.2.1 CAVE structure

The first CAVEs typically used a wood structure, since tracking systems in these CAVEs were based on electromagnetic sensors and if the structure was made of metal, it would interfere with the tracking fidelity of the system. Nowadays CAVEs use high-precision optical tracking and thus, the norm today is to use metal as the material, since it is a lot more robust than wood.

Cave structure is dependent on the type of CAVE layout and its projectors, since it should accommodate and potentialize each component of the CAVE. There are a lot of layouts for CAVEs but for projector based ones, the way of positioning the projectors are separated into two groups - inside projection and rear-projection. Inside projection means that the projectors are placed within the physical space of the CAVE, typically hanging from the ceiling or from a structure directly above the space designed for the interaction. Since the projectors are within the space of the CAVE, we must take the occlusion of projection into consideration. Projectors with high throw ratio are the less desirable because when the user is inside the CAVE interacting with a VE, his physical body may occlude the projection resulting in undesirable shadows. In this type of projector placement, ideally the best approach is to use projectors that result in the less amount of shadows produced, especially if it's a small CAVE. Rear projection, on the other hand, refers to the placement of projectors outside of the CAVE space (the image is projected in the "back" of the surface). The main advantage of rear projection is that there are no shadows in the CAVE space but comes at the cost of requiring a more

complex setup and more space readily available because they rely on a mirror system to artificially increase the distance of the projector to the projected surface. These systems of mirrors require large stands and higher precision calibration (Fig 2.6)



FIGURE 2.6: Mirror system that some CAVEs use to get the projection from outside the CAVE space.

Designing a CAVE structure, in sum, is a mix and match of what resources are available and what is that this CAVE needs to accomplish. For example if we have a 5 meter by 5 meter room, do we want a large CAVE the size of the room with inside projection (since here the space is quite large, the risk of producing shadows is small) or maybe have a 3 meter by 3 meter CAVE and have reserve the rest of the space to have supports for rear projection.

Given the above, we rapidly conclude that the structure of a projector-based CAVE must obviously take into consideration the placement of the projectors. We have several ways to deal with uncalibrated projectors, like corrective calibration software but if this work is mostly done physically, the better it is. Ideally if the image produced by the CAVE is misaligned or doesn't match as closely as possible, the CAVE should have structural mechanisms to adjust this physically to have a solid base for the calibration software to work on top of.



FIGURE 2.7: Example of a CAVE employing an inside projection method. Note the placement of the projector inside the CAVE space

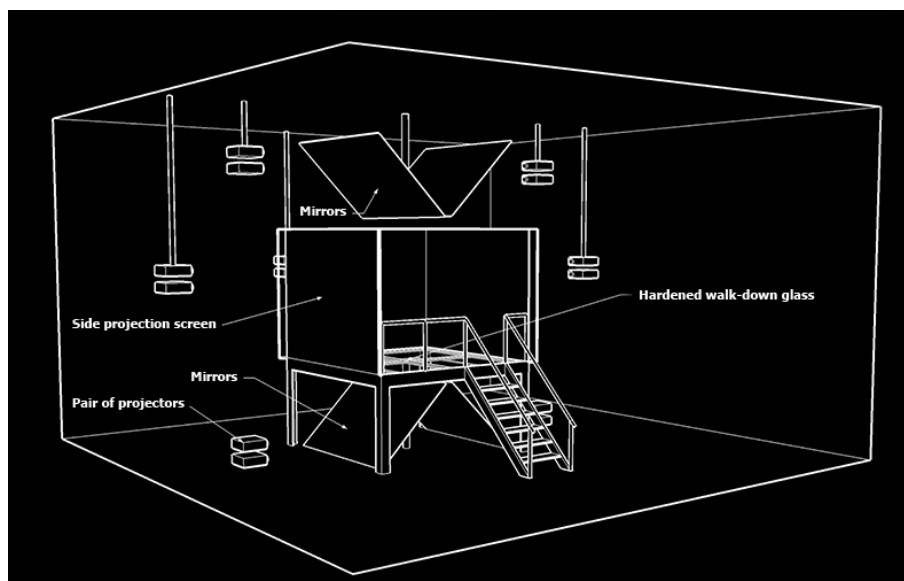


FIGURE 2.8: An example of a CAVE with outside projection. Please note the mirror system that the CAVE uses to get the projection from outside the CAVE space.

2.5.2.2 CAVE components

According to [23], a CAVE system include the following components:

Video System: The video system of a CAVE can be described by the way the CAVE presents visual content to the user. In combination with auditory and haptic displays, if applied, contribute to the generation of an immersive feeling to the user. The most common approach is through the usage of projectors but some CAVE use walls composed of LCD as employed in CAVE2. CAVE2 was developed by the same people that developed the first CAVE, and is a circular CAVE. Since the purpose of this cave was multi-user data visualization and manipulation, they came up with this 360° circular CAVE employing not projectors but LCD screens (72 screens). LCD based CAVEs have the particularity of not producing any shadows, in contrary to projector based CAVEs. This comes at the disadvantage of being quite more expensive and since the LCD screens have a small border around them, this doesn't produce a continuous image.

As is the case with trackers, projectors are also underdeveloped - they are mostly low-quality and low-resolution in comparison to the displays provided in other technologies like the PC (nowadays we have 4k resolution in PC displays). This is a trend that is explained by the greater computational power required in a CAVE, not to mention the fact that the costs quickly ramp up in a system like this. A typical CAVE has at least 4 displays and even with a multi-core approach that is present in most CAVEs, it is still less than optimal to use 4k resolution displays in CAVEs.

Let's look an example - the CAVE in [24] developed in 2012, uses **1400x1050** resolution connected to what the author describe as an image generated (probably a PC workstation) since the CAVE uses computer cluster to handle the computational requirements. The GIVA CAVE³ uses three 1280x800 native resolution projectors. Just from these two examples we can clearly see that resolution in CAVE video systems are less than optimal. Furthermore, if introducing stereoscopic rendering, the performance drops significantly as well see below.

³<http://www.geo.uzh.ch/en/units/giva/services/cave-automatic-virtual-environment.html>

Tracking System: Earlier versions of CAVEs used magnetic tracking system but nowadays that is rarely used. Nowadays, modern CAVE solutions make use of optical technology to track the user to produce an immersive system. This optical technology often comes in the form of optical infrared sensors positioned in a circle around the CAVE that tracks markers worn by the user and communicates user's position to a master node that is responsible of distributing the work of the system through various slave nodes. Most of these markers worn by the user are present in VR glasses that a lot of CAVEs use, with the added benefit that these VR glasses are needed to introduce stereoscopy in a CAVE environment.

Graphics Engine and calibration: Software for the generation of SID (Spatially Immersive Devices) are limited and difficult to come across. As mentioned several times in the length of this paper, a lot of CAVE use a clustered approach to augment the computational requirements of a demanding system like the CAVE. In other words, a clustered approach is an adaptation of standard PC engines, connected to each other through a central cluster node (called the master) that receives information and distributes the workload through the child nodes (called the slaves). Obviously, to support this networked infrastructure, special software was developed like the CAVELib. CAVELib[25] is a complete API (Application Programming Interface) for developing SID applications that features multiple graphics card integration, linking these to a unique window or viewport with view-centered calculations that corrects the output display taking into consideration the user's head position and orientation.

Game Engines have emerged and became quite popular, due to its unique platform providing greater interactivity, optimized and compelling graphical fidelity, raising also interest in developing software to handle VR applications inside these game engines. This increased popularity led research efforts into using game engines to support high fidelity VR. To support this, several softwares were developed in several game engines. For example, CryVE, developed by Juarez et al. [26] ported the high-end game engine CryEngine2 for CAVE systems, however they reported 20 average frames per second (FPS) which is not enough to support comfortable and fluid viewing experience. Jean-Luc Lugin et al. developed CAVEUDK which is a VR framework proposed to be an extension of Unreal Development Kit (UDK) to support the creation of VR applications for CAVEs in the Unreal Engine. CAVEUT was another proposed solution for Unreal Engine but its version

of Unreal Engine is now out of date and thus CaveUDK presents itself as a solution for this game Engine. BlenderCAVE[27] is the VR extension to the popular and open-source Blender Engine but reports show that its VR version evidenced low rendering performances, akin to CryVE. MiddleVR, similar to CAVEUDK, is a VR framework that offers support to the development of VR applications in the popular game engine Unity. While Unity itself is regarded as inferior to CryEngine or Unreal Engine in terms of visual fidelity potential, Unity Engine has established its place among its competitors by having a more intuitive way of learning the game engine, reduced prices and a great asset store that provides Unity extensions and models ready to deploy inside Unity applications.

A commonality of the described software above is their goal of preserving game engine performance and synchronization across the multi-display nature of CAVEs.

2.5.3 CAVE solutions

CAVE solutions differ wildly in size and characteristics but most modern CAVEs can be categorized in three groups: Professional solutions, home-made solutions and low-cost solutions.

2.5.3.1 Professional solutions

Like mentioned previously in this paper, interest in CAVE solutions has risen and today this transferred to commercial products like BARCO, Vizbox or Virtualis. In this category we encounter not only commercial solutions but also any CAVE that use state of art technology derived from pushing the boundaries of fidelity of CAVEs like the original CAVE or its successor CAVE2. Despite the rising interest in this area, current professional solutions are still extremely expensive. [28].

Let's focus on the commercial solutions for now. The three companies mentioned above (BARCO, Visbox and Virtualis) are the most well known providers of CAVE services and each provide ready-to-go CAVEs for the "naive" user of CAVE but also provide custom CAVEs tailored to customers requirements. For the focus of this paper, let's focus on Visbox and Virtualis

CAVE solutions that possess standard configurations (4 walls) backed up by information on their respective sites.

Visbox M4 is a 4 wall CAVE with interior projection (they also have a variation with outside projection called the Visbox C4) developed by Visbox that uses 4 1920x1200 resolution DLP projectors with custom projector positioners embedded in the structure. These projectors are scalable to enable stereoscopy in the CAVE with up to 10 pair of glasses to produce the effect. This model's tracking system consists of 4 optical cameras with a head marker and wand that communicates with the aforementioned optical cameras. They also include a graphics workstation with all the necessary components and cabling required to operate the CAVE. They also provide a sound system consisting of a soundbar and subwoofer. (fig 2.9). Essentially this model (as with all models in their catalogue) is the complete package in terms of commercially available CAVEs. Unfortunately the price was not available but could potentially be well over 100,000 US dollars based on the inquiries made in [26].



FIGURE 2.9: Image of VisCube M4 developed by Visbox

Virtualis ActiveCUBE: In contrast to Visbox, this company does not have specifications readily available at their website but in their brochure we can still find relevant information. Derived from this brochure, ActiveCUBE uses 4 DLP projectors (resolution undisclosed) with active stereo powered by their own PC clustering technology (Visbox uses a single workstation on their M4 model). They also provide eyewear, head and hand tracking devices which means they also use some type of optical cameras. Cost of this system was, again, undisclosed. (fig 2.10)



FIGURE 2.10: Image of Virtualis ActiveCUBE

2.5.3.2 Alternative solutions

In this group the CAVEs are categorized by being reduced versions of CAVEs or have a particular specialization that sets them apart from the typical 4-wall setup. One of them is the UT-CAVE which is a reduced version of a CAVE by possessing just 2 walls **CAVEUT** (Fig. 2.11), in which these 2 walls form a 90° angle with each other and the user is supposed to look at the seam created by the two walls, creating the illusion of a continuous image. Other interesting twists in CAVE system are the portability of such a complex system and there are some attempts made to produce a CAVE system that is easily disassembled and assembled like BARCO transportable CAVE⁴, Arcane-technologies MOBILYZ⁵ and TIVS CAVE[29].

⁴Transportable CAVE by BARCO

⁵MOBILYZ CAVE by Arcane-technologies

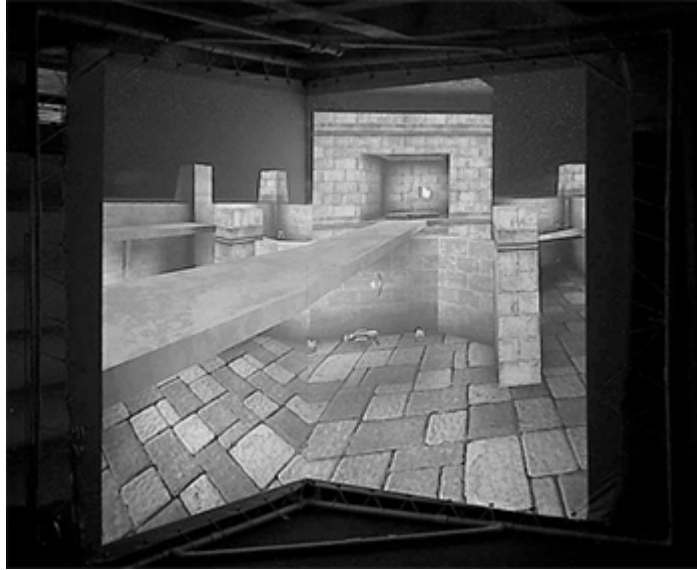


FIGURE 2.11: Overhead image of UT-CAVE with just his two walls

The BARCO transportable CAVE is a commercial solution that uses a 2 side surfaces and a floor for projectors. What makes this CAVE portable is that fact that major components like the projectors, projectors mounts, mirror (for rear-side projection) and surfaces are embedded into a container that stands on wheels (with the ability to lock said wheels). The floor surface can be stored in one of the side containers for transportation. This CAVE is depicted on Fig 2.12). While this is one of the best attempts at creating a portable CAVE, the containers are big (3,16 meters wide by 2,44 meters tall) and may be cumbersome to transport such large containers.

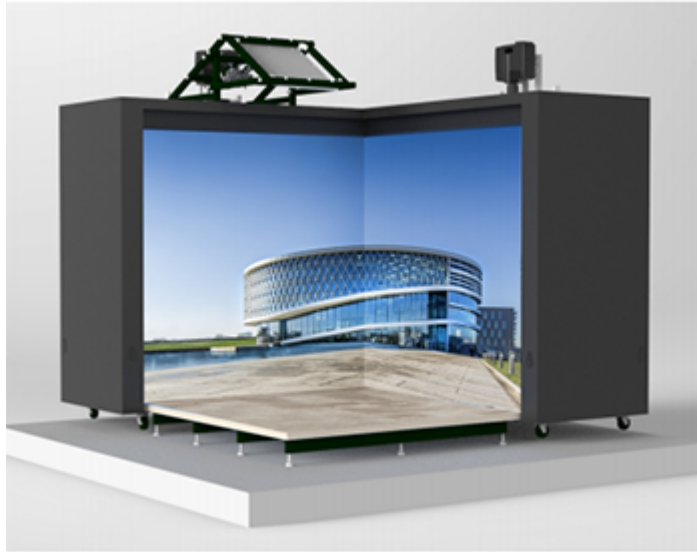


FIGURE 2.12: BARCO transportable CAVE

TIVS[29], or short for Temporary Immersive Virtual System is a CAVE developed by Wolfgang Stuerzlinger et al. in which the core idea is to have a CAVE that does not consume permanently floor space. They accomplished this by having a ceiling mount that has all the major components of a CAVE and the walls of the CAVE are rolled up (See fig 2.13) or down depending on the necessity to have the CAVE in operation. In other words, when the CAVE is not being used, the screens are rolled up into the ceiling mount, freeing the space below said mount and when the CAVE is in operation, simply roll down the screen and turn on the system. This is an interesting approach that focus not in transportation on the system but the rather the economization of the space for other activities. (The deployed CAVE is depicted in fig 2.14).



FIGURE 2.13: Depiction of the roller screens used in the TIVS CAVE. When the CAVE was not in operation, these roller screens allowed for screens to be collected and the space beneath the CAVE to be free for other uses.

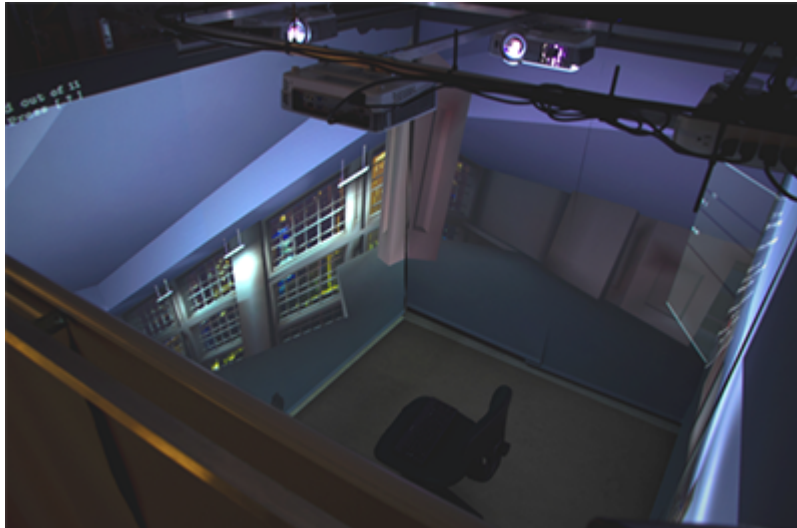


FIGURE 2.14: Overhead image of a deployed TIVS CAVE

2.5.3.3 Lost cost solutions

Professional solutions delivers impressive visuals, high precision tracking, unparalleled modeling and rendering but all of this comes at prohibitive costs. As CAVE technologies matured, low-cost approaches have appeared as a response to the need of filling the gap between state of art professional solutions featuring stunning visuals and unparalleled tracking and cost effective (but using outdated technology) open source systems. The objective of low-cost systems is to match the fidelity of professional solutions while keeping the costs as low as possible. While its tempting to immediately compare the cost of these low-cost CAVEs and other technologies (like HMDs that cost around 1000 dollars described in section 2.4), the term low-cost here does not automatically warrants that it is affordable for any medium-sized institution, it simply means that is a much cheaper compared to CAVE standards.

The original CAVE[22] was a professional solution with a whopping 2 million dollars in development costs. Green and White estimated in the year 2000 that a **low-cost** CAVE system was around 100,000 euros [30] so we're talking here about a 8 year time span and very substantial decrease in costs. Fast forward to recent years, the 2012 CAVE2 **professional CAVE**[31] costed approximately 926,000 dollars while the 2009 CryVE low-cost CAVE [26] was around 19,300 euros (22,800 dollars at the 2017 currency exchange rate).

The CryVE CAVE [26] like previously mentioned, is a CAVE developed to accommodate the CryVE software. They report in their paper that they contacted three commercial companies inquiring about the price of their custom

CAVEs that fit into their requirements and got two responses of 160,000 euros and 630,000 euros which they deemed too expensive for their budget so they looked into ways of reducing the costs. Obviously there is a profit margin in commercial CAVEs and their price is not reflective of the production costs. They found ways of reducing costs in major components of CAVEs and the components that had more margin to push the price down was the structure and the CAVE software (which they developed in-house). Like reported above, the cost of this CAVE was 19,300 around (Fig 2.15). One important aspect to note is that this CAVE did not possess a tracking system that is present in a typical CAVE and thus, the price is subjected to be higher if such a system was to be implement, even more so since the current tracking solutions are quite expensive. They calibrated the CAVE images by feeding their CryVE software a fixed viewing position that corresponded to the center of their cubic shape CAVE.

Item	Cost (EUR)
Canvas	6700
CAVE structure	3600
PCs	4600
Projectors	4100
Networking and other materials	300
Total	19,300

FIGURE 2.15: CryVE cost breakdown by components

It's worthy to mention the cost of TIVS CAVE[29] mentioned in the subsection 2.5.3.2. This CAVE was categorized as an alternative solution because of its novel way of deploying and concealing a CAVE system as well as its outdated technology but despite this, it has a relatively low-cost of 9,500 US dollars. They reported 4,900 US dollars as the cost of the CAVE not taking into account the PC they already had in the lab (1,100 US dollars) and the NaturalPoint OptiTrack cameras they used for body tracking (3,500 US dollars). (See Fig 2.16 for their breakdown of costs of the aforementioned 4,900 US dollars system)

<i>Item</i>	Cost, US\$
Projectors	4,000
Screens	400
Aluminium tubing	150
Fasteners	50
Steel cables, pulleys, winch	150
HDMI cables, extension cords	150
Total	4,900

FIGURE 2.16: TIVS CAVE cost breakdown by components, not including tracking and workstation price.

Now that we've discussed CAVE solutions in each of the CAVE categories described in the literature, in the next subsection we present differences and areas of expertise between the two most used systems to implement immersive VR systems - CAVE and HMD.

2.6 Comparing Head Mounted Display and CAVE

While both are means to implement Virtual Reality by providing real-time viewer-centered displays, these two offer two different immersion and sensory fidelity

Head Mounted displays has drawbacks in the form of low field of view (HTC VIVE has 110°) while most CAVEs in contrast have wider field of view (170° - 180°) in standard 4 four wall CAVE or even 360° in circular CAVEs (CAVE2).

In CAVEs, the user isn't as disconnected from the real world compared to HMD and the perception of the user that his body is actually "there" inside in the Virtual environment combats real world isolation. By real world isolation we refer to the fact that users are completely separated from the the real world (which happens in HMD) and this leads to highly disorienting systems. A study by Kim [21] point that the lack of an avatar in HMD increases the cause of nausea in users.

Another limitation that HMD have is the fact that multiple people cannot share the same virtual experience simultaneously. In fact, the first CAVE [22] was developed to overcome this limitation and allow several people inside

the CAVE interacting with the VR environment.

In terms of comfort, the CAVE clearly wins in this one as its much more bearable to be in a CAVE for several hours. In contrast, wearing an HMD for several hours leads to ramps in discomfort very quickly due to several factors, like the weight or the heat generated by the HMD.

In figure is a high-level review of differences between HMD (Oculus Rift) and a professional CAVE solution (VisCube CAVE)

	Oculus Rift HMD	VisCube CAVE
Resolution	~1 Mpixel per eye	~2-8 Mpixels per screen
Image Quality	requires distortion and color correction	pixel perfect
Immersion	completely immersive	immersive
Field of View	100 degrees	170 degrees
Presence	disembodied, isolating	excellent, see your own body
User Volume	movement limited due to isolation, tether, and small tracked volume	completely wireless, precise tracking, move around freely in user volume
Users	single user	multiple viewers, one tracked user
Comfort	bulky, tethered, sweaty	lightweight glasses, wireless
Small Group Collaboration	not well suited	ideal for face-to-face meetings
Tracking Error/Latency	sensitive, simulator sickness more likely	much less sensitive, simulator sickness less likely
Accommodation	close screens cause eye discomfort over time	large, fixed screens comfortable with extended use
Cost	very low cost	high cost

FIGURE 2.17: Table depicting some differences between HMD and CAVE, credited by Vibox⁶

Consolidation: CAVE systems excel in scientific, engineering and data exploration applications in a collaborative environment in which the CAVE provides engineers, scientists or managers the ability to work together in

the same VR applications. HMD excel in single high-end graphical fidelity application with entertainment in mind.

2.7 Assessing Virtual Reality systems

Let's look at some ways that have been used to access virtual reality systems. As we have previously seen, presence and immersion are two very important dimensions to measure virtual reality systems. [10]

2.7.1 Presence measurement

The importance of developing approaches to measure presence have come to prominence lately because of many important research endeavors that have been hindered by the absence of said approaches. Since researchers took notice of this void of a standardized measure of presence, many researchers came with a different ways to create a standard measure of presence. Throughout this document, emphasis has been put into the definition of presence being a subjective dimension. While this is true, presence can also be objectively assessed. So firstly, let's look at objective approaches to measure presence.

Objective measurement of presence: With the rise of bioinformatics that use sensors to register a wide array of physiological sensors[32], researchers found a purpose to apply these to the objective measure of presence. One objective approach that researchers investigated was measuring presence with basis on levels of skin conductance response (SCR), heart rate, blood pressure, respiratory levels, muscle tension (using something as the Myo Gesture Control Armband⁷). While there are little empirical studies relating these measurements related specifically with presence, such a way has been proposed by Wiederhold [33] in which they investigated the effects of varying levels of overall immersion in a flight simulation, comparing a computer screen to an HMD using a conjecture of subjective presence rating obtained through questionnaires and physiological measurements of heart rate, SCR, respiratory rate and skin temperature. Of all of these physiological measurements, only SCR proved to have a weak link to arousal (described in the

⁷<https://www.myo.com/>

behavioral realism paradigm[34]) but had insignificant impact on overall immersion.

Subjective measurement of presence: Contrary to objective measures, subjective measurement of presence is far easier to extract information from since there are no complex sensors to setup which may or may not be prone to failure or wrong readings (depending on the calibration). Inside this subjective approaches, there are some that do not involve validated questionnaires such as informal interviews, the use of focus groups or ethnographic observation. Since these methods are not validated they are prone to produce data low in reliability and difficult to produce knowledge from.

Presence questionnaires are the most widely used method to measure presence. Measuring presence through the use of user-centered questions lead to potential very useful information, as the quantification the user experience allow defined and concise statistical comparisons. Some attempts have come up to develop validated questionnaires to assess test different hypothesis related to different contexts and as such, there is a lack of a standardized self-report measure of presence. But what do we mean by saying standardized questionnaire? There are some criteria that must be met to allow comparisons across media, subject groups, fields or contexts. These questionnaires must be:

- **Reliable**
- **Valid**
- **Sensitive**
- **Comprehensive**

Firstly, reliability of a questionnaire is the extent that the questionnaire is free from error and produces consistent information over different applications. [35]. Consistency is used here as a way of describing the task of producing the same information in which a medium has not changed. In other words, if I make a study two or three times in a row where nothing has changed, does it produce the same data? This is reliability. Of course, taking the same study twice it will be very difficult to have exactly the same information. These variations, if linked to physical performance rather than measurement error, we say that the questionnaire is free from error.[36]

Secondly, a presence questionnaire must evidence some form of validity, including corroboratory data, correlation with other presence measures, like objective measures described above, correlation between items of the questionnaire convergent data between what the questionnaire is measuring and other measures theoretically linked to presence and known comparison studies done by other researchers. This is summed up by five distinct types of validity evidence: Evidence based on test content, evidence based on response processes, evidence based on internal structure, evidence based on relations to other variables and evidence based on the consequences of testing. [37]

Next, the third criteria is that a questionnaire must possess some type of sensitivity. This means that, changing a variable that influences a certain term in the questionnaire, this in turn, must be able to detect this change.

A presence questionnaire must be comprehensive, operating at the extent of the multiple layers of the concept of presence - the six conceptualizations described above. It should identify between these multiple conceptualizations. Presently, very few questionnaires assess all dimensions of presence, since presence is very vast and context-dependant. More on the construction of a questionnaire taking into consideration all of the described above see [10].

There are a a lot of questionnaires (see [38] for more than 25 presence questionnaires), but let's conclude this section of presence questionnaires taking a look at three prominent questionnaires. These are the Slater-Usoh-Steed(SUS) questionnaire, the Witmer presence questionnaire(PQ) and the Igroup presence questionnaire(IPQ).

Slater-Usoh-Steed(SUS) questionnaire: This questionnaire also known as SUS was made by Slater and his colleagues[39] based on their research and terminology. As previously seen, Slater tried to separate immersion and presence and his definition of presence is based on the conceptualization of transportation. As such, the questionnaire that he developed, naturally contains questions that try to assess this sense of transportation. The SUS is a five item short questionnaire that has been widely used in a large number of presence studies. In terms of validity, this questionnaire was found to correlate strongly with objective measures of presence in various studies. In the pilot study by Slater, he was using his questionnaire in a real environment (an office) and a virtual environment which mimicked the real one. In this

pilot study the results show no significant difference between the real and virtual environments, so it was reported as a low level of sensitivity.

Witmer presence questionnaire(PQ): The proposal of this questionnaire arose in 1993 by Witmer and Singer[40] and nowadays is the most widely used presence questionnaire. It assesses two dimensions of presence, namely presence as immersion and presence as realism described in section 3.5.2. The authors described the questionnaire as highly reliable. Also, they conducted four experiments to determine the validity of the questionnaire by correlating the questionnaire with other objective and subjective measures of presence and they reported significant correlations. In terms of sensitivity the PQ, the two studies they conducted result in significant distinction between the high and low presence conditions they imposed in their study.

Igroup presence questionnaire (IPQ): This questionnaire was developed by combining the SUS, Claudia Hendrix presence questionnaire [41] and Regenbrecht (the author of IPQ) research [42] and resulted in a 14-item assessment tool. By combining aspects of SUS and PQ, the IPQ assesses all three dimensions of presence that are relevant for VR-related studies- presence as immersion, presence as realism and presence as transportation. Pilot studies using IPQ indicated high level of reliability and sufficient level to demonstrate IPQ validity. According to [42] IPQ was found to have sensitivity by distinguishing multiple layers of presence.

Chapter 3

KAVE - proposed CAVE

Taking into consideration the analysis of the CAVE work that has been done in section 2.5, we notice that a lot of CAVE solutions are permeated by complex setup or prohibitive costs (easily reaching hundreds of thousands of dollars) and pushes back availability of this technology to a lot of developers or VR enthusiasts. We noticed the opportunity to extend the work done in the field by developing a CAVE solution that softens the complexity of setting up a CAVE at a comparatively affordable price.

In this section we describe our proposal for a low-cost CAVE, named the KAVE. This CAVE was implemented at M-ITI(Madeira Interactive Technologies Institute) located in Madeira, Portugal. This solution tries to minimize costs while trying to retain maximum quality and performance compared to professional solutions.

Our proposed solution consists of a physical CAVE and its components (display technology, tracking and CAVE software). In the following sections we describe in depth each component of the KAVE and well as the CAVE calibration software and process.

3.1 KAVE Design

Firstly, let's discuss the structure of the CAVE.

The stability of the CAVE structure is very important since any instabilities could cause the CAVE to lose the calibration over a long period of time, requiring a new calibration process every time it breaks the calibration. Instabilities in the structure of the CAVE could also cause the CAVE to ultimately collapse. Taking this into consideration, we ultimately chose a structure made of galvanized iron. We mentioned previously the dangers of using metal structures with magnetic trackers but since this CAVE uses optical tracking, the material of the structure is irrelevant in this situation.

Galvanized iron is robust enough to support the weight of the projectors and make sure they stay in place over long periods of time. The disadvantage of this material is that since it isn't stainless, it's prone to rust occurring in the structure.

With the material chosen we defined some requirements that this structure had to accomplish. Such requirements are as follow:

- The structure must allow adjustments in the projector distance from the floor.
- The structure must allow adjustments in the projector distance to its corresponding projected surface
- The structure must allow the aforementioned adjustments without the need to disassemble the structure
- The structure must remain stable after performing aforementioned adjustments

Analysis: A structure that allows to easily adjust projector placement in 3D space is a big advantage because placement of the projector is extremely important to get an undistorted image as well as maximum resolution. The projector placement is important to consider because of one particular property that is called the *throw ratio* of a projector. *Throw ratio* of a projector refers to the amount of distance the projector needs to "deliver" the image to a particular image width. So if a CAVE wall is 3 meters wide, this distance must be taken into consideration to correctly place the projector at a distance that the image produced by the projector is as close to 3 meters in width as possible.

A CAVE structure that intrinsically allows adjustments regarding the projector distance to the wall without disassembling parts of the CAVE grants some of the complexity of placing the projectors to be taken away and ultimately is an important step in setting up a CAVE easily.

In our effort to reduce the costs associated to CAVE ownership and taking the previous list into account, we assembled our own custom solution - the structure to support the projectors and surfaces of projection.

3.1.1 KAVE metal frame

The space to deploy the CAVE was reduced (3 meters wide by 3 meters length) so we conceptualized the CAVE to be 2.8 meters in wide and 2.8 meters in length. In figure 3.1 we can see the conceptualization of the KAVE in

the form of a computer render. To achieve the requirements in the aforementioned list we idealized the vertical corner beams of the CAVE with several holes, separated by 15 centimeters, to allow the insertion of a bolt at the desired length that as we can see in figure 3.4. All of the CAVE beams are 46 millimeters interior diameter.

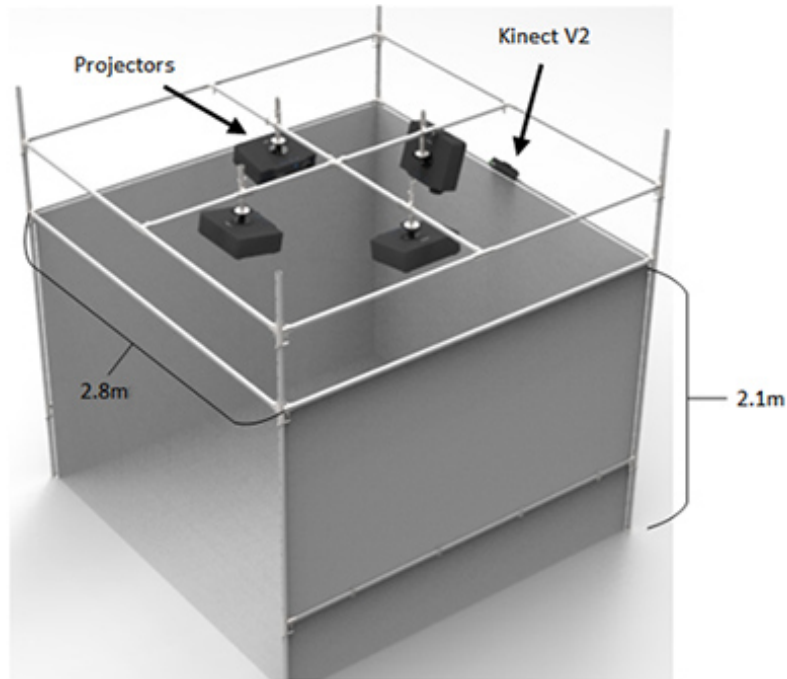


FIGURE 3.1: Render of the physical structure of the KAVE

The intersections of the metal (Fig 3.2) were made also of galvanized iron with 48 millimeters interior diameter to allow the support beams to slide inside along these metal pieces (see Fig 3.3). Holes were made in each arm to allow fixation with a bolt to the support beams. As we have seen in the initial render (Fig 3.1) we can say that there are 3 horizontal layers of metal. The first two counting from the ground holds the horizontal and vertical shape of each CAVE wall. The third layer of metal is the layer that has the projectors. The projectors are hold in place by a clamp metal piece that when unscrewed allows the whole projector structure to slide along the metal tube. The vertical projector metal tube also allows the projector to slide vertically to further push this *physical projector calibration*, as seen in Figure 3.5.



FIGURE 3.2: Metal intersections used to hold the beams together



FIGURE 3.3: The 3 layers of metal depicted in this figure can be slid along the vertical beam and fixed in place with a bolt. Please note these vertical beams are depicted on Figure 3.4

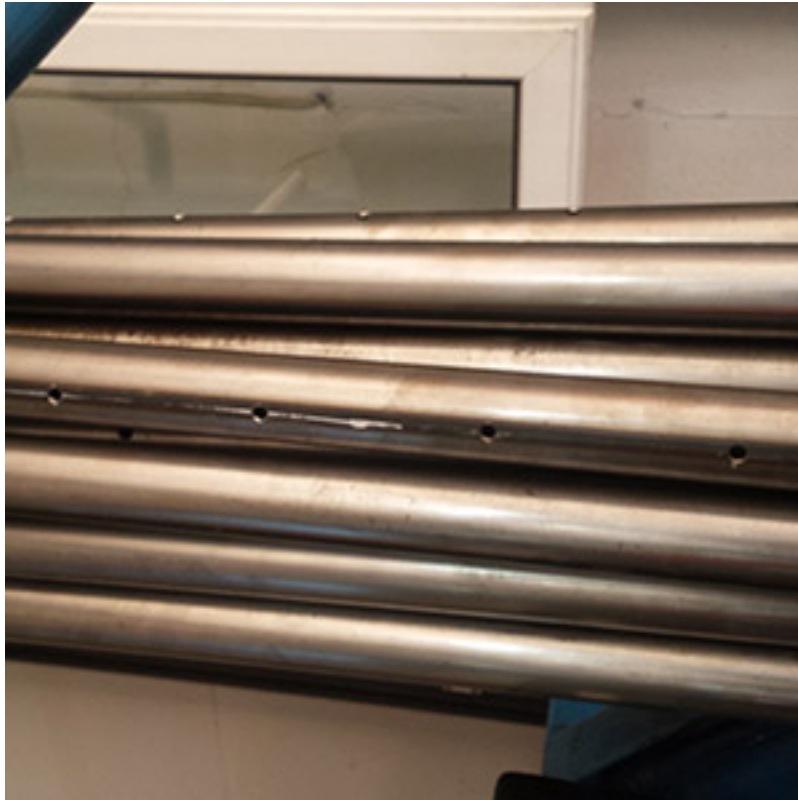


FIGURE 3.4: Corner pillars of the CAVE showing bolt holes



FIGURE 3.5: Custom projector mount system used in KAVE.

3.1.2 KAVE walls

Now that we've looked at the metal frame of the CAVE let's discuss the thought process that went into the CAVE walls.

Initially we had pondered to use a modified commercial white canvas like used in presentation rooms (similar to a white board) and have it adjusted to the CAVE frame. The problem with this approach is that it is not accident tolerant. Say, if someone were to accidentally apply pressure to the canvas, derived from a fall for example, it could tear the canvas. Our strategy was then to have some sort of robust wall that wouldn't tear easily. This culminated in the choice of having wooden walls fixated to the metal frame, because they offer the resistance to user accidents and was easy to setup. At our local retailer we found wooden plates 1.2 meter wide by 2.4 meter tall and since each wall was 2.8 meter wide we needed three plates per wall to cover the wall width reaching a total of 9 wooden plates for the three walls of the CAVE.

The disadvantage was that rough wood is not ideal for projection - we needed a clean, white surface to project on. Our strategy to circumvent this issue was to apply a mixture of stucco and plaster to hold the wood tiles together (reminder that each wall has 3 wooden tiles), hiding imperfections such as perforations made by the bolts as well as leveling the surface - resulting in a smooth surface. With this work done it was only a matter of applying white paint to the resulting surface.

Figure 3.6 depict the process. The first image in figure 3.6 shows our solution to fixate the wooden walls to the metal structure. The second picture shows a white layer of platers applied vertically to cover the intersection of two wooden tiles. In the third picture we also have a part of the plaster application process. The plaster was also applied to dark wooden spots derived from the vein of the wood itself, as well as to cover bolt holes and nicks in the wood. The fourth picture shows the painting process that was performed after all surfaces were leveled and smooth. Four white layers of paint were applied in this process. The fifth and final image in figure 3.6 shows the KAVE after all three surfaces were painted. The white-canvas material floor was posteriorly placed correctly in place.



FIGURE 3.6: Sequence of images depicting the process of establishing the CAVE walls

3.2 KAVE tracking technology

In subsection 2.5.2.2 we discussed optical sensors and how they possess high accuracy, however this comes at a price - High costs (For example A.R.T trackpad4 system, which consists of 4 optical sensors, is over 2000 euros). In the case of solutions combining optical sensors tracking wearable technology on the user, a disadvantage is also the lack of comfort derived from having these types of wearable technology. To combat these disadvantages - high price and lack of comfort - our strategy was to have a CAVE that doesn't push uncomfortable wearable technology into the CAVE user by means of using a single Microsoft Kinect V2 for tracking. The Kinect is also an optical sensor, more specifically an infrared (IR) emitting sensor that not only can track the head of the user like previous mentioned solutions but also the whole body.

To produce body tracking inside a CAVE, basically there are two ways - have the user of the CAVE wear a motion capture suit equipped with retro-reflective markers and calibrating the CAVE for user's body size, or using something like the Kinect that tracks the user's body independent of its size without the need to wear a motion capture suit. Obviously the former way is not ideal for a low-cost solution, making the Kinect a very tempting solution.

One could argue that body tracking is only important if the CAVE will run applications that require the body to interact but with the Kinect coming at an affordable price (One Kinect costs about 200 euros), is a way of having a CAVE that is scalable to run VR applications that not only adjust the image based on the user's head (like other solutions) as well as potentially use the user's body as an interaction method.

Choosing a Kinect for tracking has its disadvantages - one being the precision of the tracking compared other tracking solution (described in). Like mentioned in section X, this lack of precision could be improved by using multiple Kinects but ultimately we did not choose this route because it would indulge in more complexity and additional costs (monetary and computational) which defeats the purpose of our proposed solution.

This comparatively inferior level of precision of using a single Kinect inside a CAVE is also due to the fact that the Kinect can sometimes "lose" the user derived from him getting out of the Kinect field of view (FOV). To attenuate this, the Kinect was placed above the middle of the front wall at a 30° downward angle. This position is the one that covers the most CAVE space

in KAVE.

3.3 KAVE software

Calibration of projectors are always needed for a number of different reasons, whether it is because of overlapping projections or image distortions. Since one of the proposed goals is to reduce the complexity of setting up a CAVE and calibrating projectors manually is very hard, a calibration software - called KAVECam - was developed.

KAVECam disassociates the position and orientation of the projector from the generated image by the projection. In other words this means that as long as the projected image is larger than the projection surface, through the implemented projection mapping, a continuous image can be achieved across all surfaces with arbitrary projector placement and thus no longer requiring extreme precision placing the projectors inside of the CAVE. The software outputs the position and orientation of CAVE projectors as well as the CAVE sensors and stored them into an XML that subsequently feeds into a Unity plug-in called *KAVE plug-in* that instantiates a virtual CAVE based on the XML information to use in any Unity game or software.

In this section we elaborate on the features of KAVECam, it's architecture, components and an example of a use case to facilitate comprehension of its usage and advantage.

3.3.1 KAVECam overview

KAVECam was developed in Unity 5.5¹, and its desirable function only works in Unity applications. VR applications made in other game engines (like CryEngine² or Unreal Engine³) are not supported by KAVECam. For the rest of this thesis, when discussing KAVECam applicability let's assume a VR application developed in Unity.

Unity was chosen because of it's developer friendly and provides a wide range of support, not to mention it is the platform that NeuroRehabLab, where this thesis is inserted, operates.

¹www.unity3d.com

²www.cryengine.com

³<https://www.unrealengine.com/>

In the introductory paragraph of this section, we mentioned that KAVE-Cam is a CAVE software which the main objective is to calibrate a CAVE - but this is too vague of a description so let's elaborate.

As we have seen in the literature, motion parallax is an important feature in CAVE systems. This motion parallax effect is achieved by accurate tracking of the user point of view and the projection of images correspondent with that point of view. A good analogy is to imagine if the user was literally inside the virtual environment, what would he see in the CAVE FOV. By knowing the user point of view, or rather, its head position (tracked by the Kinect) and the position of the projection planes (described in the output XML of KAVECam), we can produce images on those planes correspondent to the user's point of view.

Thus, to correctly produce a parallax effect and display images on the CAVE walls in relation to what the user should see if the virtual environment was real, each component that takes its part in achieving this - extrinsic and intrinsic parameters of CAVE projectors, position and orientation of CAVE walls as well as tracking system - must be represented in a good calibration software.

KAVECam offers projector calibration in a two step stage:

1. Image distortion correction
2. Confinement of projected image to projection surface

3.3.1.1 Image distortion correction

KAVECam calibration is meant to give information to Unity Camera parameters. Unity Cameras, like its name indicate, are Unity objects that it is used to "view" the virtual world. In other words, KAVECam is a cluster of up to four Unity Cameras with corrected parameters that mimics the real life projectors of the CAVE. If this does not happen, it results in image distortion, because the position of real life projectors' distance to the CAVE walls is not portrayed in the Unity Cameras, resulting in incorrectly rendered images in relation to users point of view.

Our strategy to resolve image distortion is then to have a feature that lets the user setup the Unity Cameras and match their virtual position (X,Y,Z coordinates) to the position of the real world projectors. In other words, if real world projector designated A, is 2 meters from the ground up and 2 meters from its designated projected surface, KAVECam allows you to setup

a virtual Unity Camera that is 2 meters from the ground and 2 meters from its designated projected surface.

However, even with matched positions, this does not guarantee that the image is undistorted. Other parameters must be considered. These parameters (called intrinsic parameters) are field of view of each camera (FOV) and vertical lens shift that the projects in the KAVE use. These must match as well.

3.3.1.2 Confinement of projected images

Like mentioned previously, one of the advantages of KaveCam is that it allows arbitrary placement of the projectors as long as the projected image covers the surface that is receiving that projection. To achieve this, our strategy is to simply clip the "excess" projection in a way that the projection is confined in width and height to the projected surface.

One way to achieve this is by sending the projectors color information about the areas that we want to trim down in the form of pure black (RGB 0,0,0). In common knowledge, black is associated with the absence of light and this same logic applies in this situation. By imposing pure black in the areas we want to trim the projection, we are signaling the projectors to disregard the light (and therefore any type of color) in those areas.

3.3.2 KAVECam architecture

Now let's analyze a high level architecture of KAVECam. KAVECam architecture is a fairly simple one where it was two main software components: KaveBuilder and CameraMapper.

Firstly, figure 3.7 depicts the high level architecture of the system. The communication of the Unity Camera components with the connected displays are established by the operating system and Unity itself.

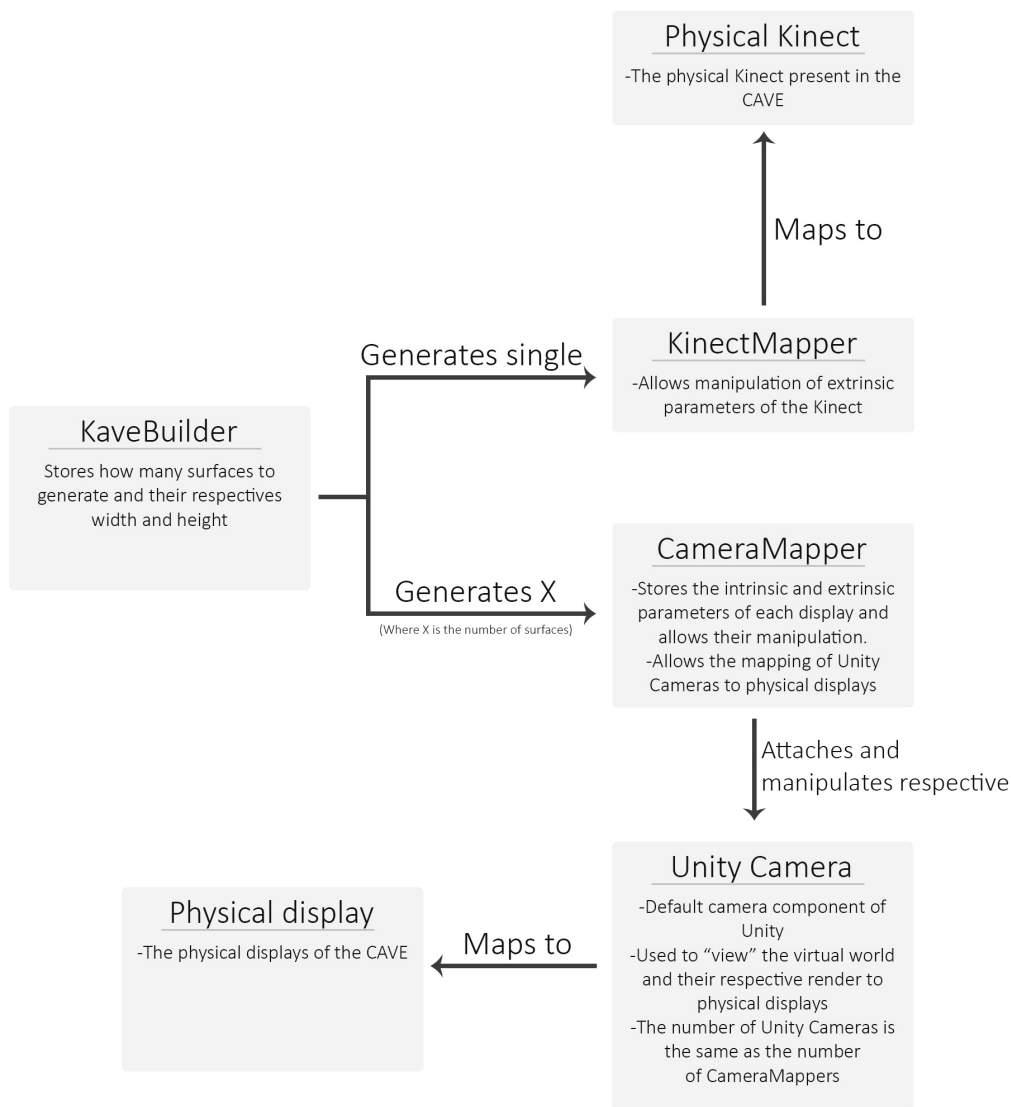


FIGURE 3.7: KAVECam Architecture

3.3.2.1 KaveBuilder

KaveBuilder is responsible for building the virtual CAVE in Unity and for all parameters of the surfaces of the CAVE. It stores each wall width and height which are inputs given by the user and assumes a thickness of 1 centimeter for each surface. It also encompasses a GUI that allows users to select any four surface combination, meaning you can build virtual CAVEs with one, two, three or four surfaces with any given combination from the following: Left Wall surface, Right Wall surface, Front wall surface and Floor surface. This is depicted in Figure 3.9. For each wall that is selected in the GUI and given a width and height, the software generates a Unity camera

for that corresponding surface and adds a CameraMapper component to it.

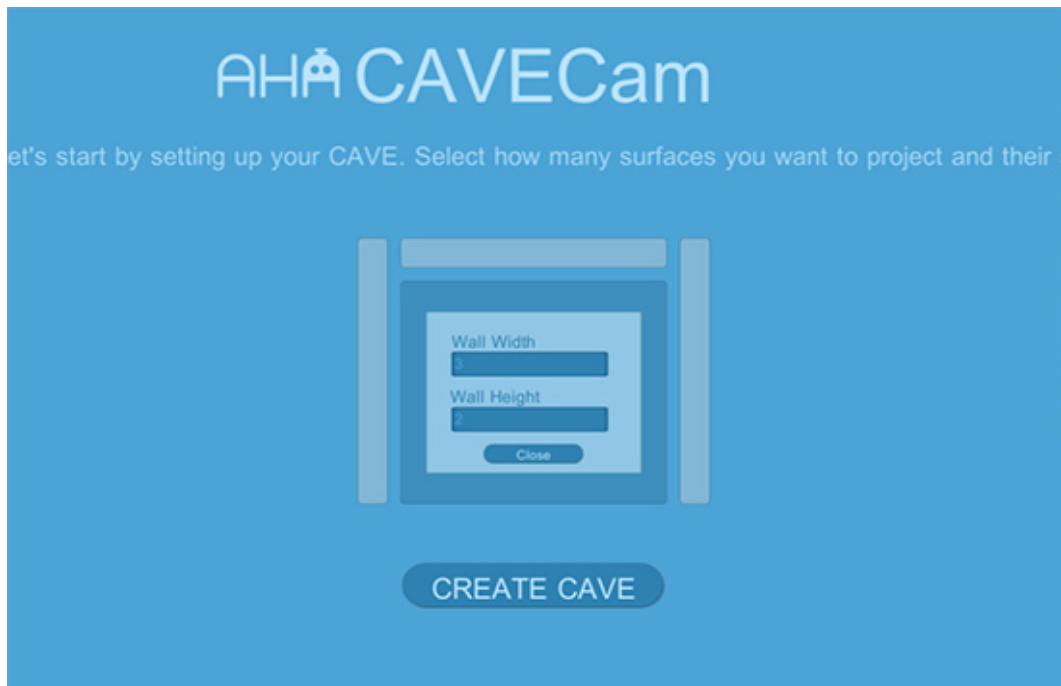


FIGURE 3.8: KaveBuilder component graphical user interface

As previously mentioned the layout of the CAVE can range from any combination of 4 surfaces and this selection is possible simply by selecting which surfaces to be created in the GUI(see Figure 3.9. To correctly place the surfaces in the real world independent of each wall size, a referential was needed. The referential chosen was the bottom left corner of the CAVE and the desired walls to be created are positioned accordingly. This produces the advantage of correct placement of walls inside the virtual walls in non-standard wall dimensions, for example a front wall measuring 4 meters wide by 1 meter tall in combination with a left wall 3 meter wide and 7 meters tall.

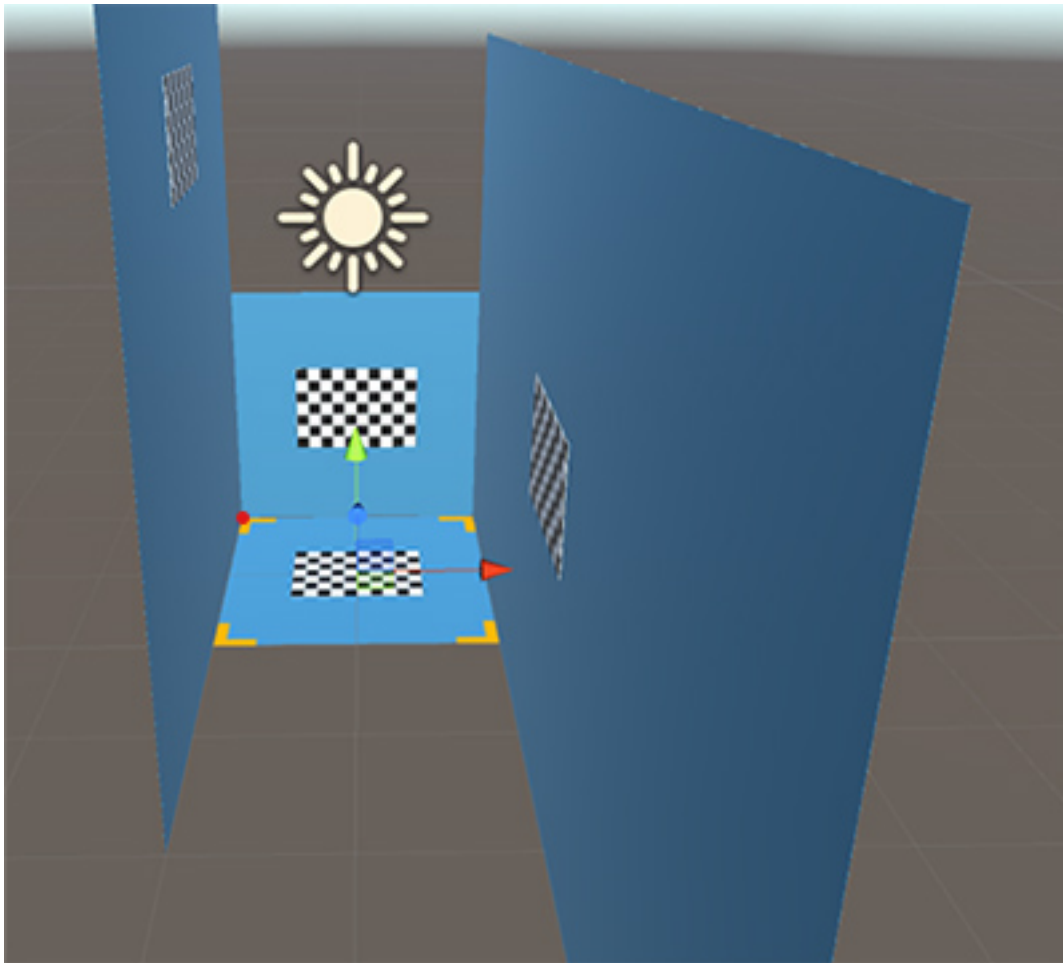


FIGURE 3.9: A non-standard configuration CAVE where the side walls have different width and height from the front wall. The red circle depicts the referential

3.3.2.2 CameraMapper

CameraMapper is responsible for changing and storing the intrinsic and extrinsic parameters of each virtual camera (each corresponding to a CAVE projector). Each virtual camera has its own CameraMapper and is independent of other CameraMapper. A GUI is attached to the CameraMapper (see Fig. 3.11) with various sliders that when operated change these parameters.

Another important component is the KinectMapper. It is identical to CameraMapper but with less functionalities since to calibrate the Kinect in this environment we only need position and orientation of the Kinect. These values are stored in the KinectMapper.

We've seen that KaveBuilder, CameraMapper and KinectMapper store values, and these may be save or loaded at will through a Saver and a Loader component. The Saver component, when called looks at KaveBuilder and CameraMapper stored values and outputs these in .xml file extension. Similarly the Loader component reads an .xml file extension (the name of the file is given by the user) and loads each value into the correct fields.

3.3.3 KAVECam calibration procedure

To facilitate comprehension let's describe a scenario where Justin (fictional name) is a software developer for Unity and invested in a CAVE. His CAVE is a four surface layout (left wall, right wall, front wall and floor) and for demonstration purposes let's assume he has only one projector per wall. Each surface measures 3 meters in width and 2 meters tall:

1. **Left wall** : 3 x 2 meters
2. **Right wall** : 3 x 2 meters
3. **Front wall** : 3 x 2 meters
4. **floor wall** : 3 x 2 meters

With all projectors turned on, he runs KAVECam. In the menu he doesn't want to load any CAVE since he doesn't have an .xml file that the Loader component can read. He wants to create his virtual CAVE so he clicks the *Create Cave* button. This takes him to KaveBuilder GUI. Since his CAVE has four surfaces he goes through each surface and types its width and length. In this case it is 3 meters width and 2 meters length (see figure 3.10). After making sure the values are correct he clicks the KAVEBuilder *Create Cave* shown in figure 3.10

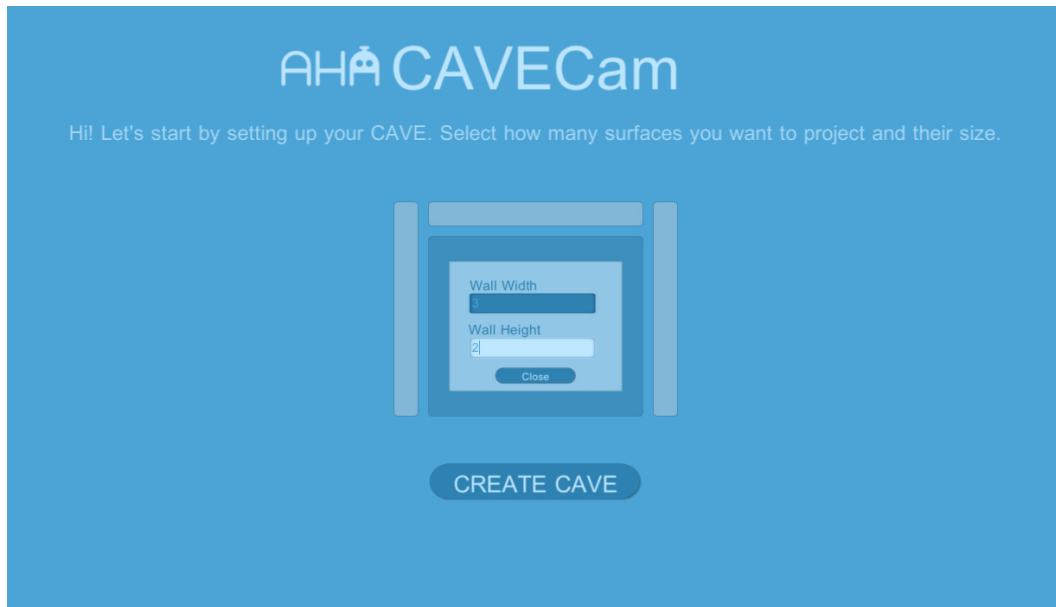


FIGURE 3.10: Input of the dimensions of that floor surface

In the background, KaveBuilder stored Justin's surface values and created four planes with the dimensions Justin specified at corrected orientation as well as Unity Cameras that have all intrinsic and extrinsic parameters of the Unity Cameras set to 0 (except for field of view, which the default is 60). The default selection is the left camera so Justin starts by calibrating that. First of all, Justin doesn't forget to assign the left Unity camera to the display number (See figure 3.11 corresponding to the projector that is projecting to the left wall by choosing the display number from the *Display* dropdown menu. He knows his projectors are 3 meter high in his CAVE so he types in the *Y slider input box* the value 3. Now using the orange corners that are projected in the left wall, Justin tries to match these orange corners to the corners of the real life CAVE left wall, using the various sliders that KAVECam provides. After finding the calibration of this projector satisfactory, he repeats the process to all the other projectors.



FIGURE 3.11: Note the mapping of "Front Cam" (Front Camera) to "Display0". Also note the *Load*, *Save* and *Kinect* buttons present as well as the various sliders used to manipulate the intrinsic and extrinsic parameters of selected camera

Now it's time to calibrate the Kinect. Firstly, Justin toggles the *Kinect* button in the CameraMapper. This hides the CameraMapper and pops up the KinectMapper (see figure 3.12). In the KinectMapper Justin clicks the *Toggle view* button to switch to the Kinect POV. Two red squares are now being projected on the floor (It's important to have the floor calibrated first to get an accurate representation of the square boxes). Using the sliders, he matches the two red squares to both his feet. This ensure that the position of the "virtual" Kinect inside KAVECam matches the position of real-world Kinect that is in his CAVE.



FIGURE 3.12: GUI used to manipulate the extrinsic parameters of the Kinect. The orange box is the virtual depiction of the physical Kinect

With both projectors and Kinect calibrated it's time to save this calibration by using the *Save* button. As mentioned before, this outputs and .xml file in the *Streaming Assets* folder of the KAVECam folder.

KAVECam job stops here, however it is important to notice that the .xml true purpose is to feed KAVE plugin to setup a virtual CAVE to use in Unity games and applications. After finding a good test Unity scene for his CAVE, he imports the KAVE plugin in his project and this plugin now makes use of Justin's .xml file. (See ⁴ for more information on KAVE plugin.)

3.3.4 CAVE Comparison

In this subsection we present a comparison in terms of immersion (as defined in 2.3) between our proposed solutions and other low-cost solutions found in the literature (described in subsection 2.5.3.3), as well as a price comparison. Firstly we present a taxonomy table in Fig 3.13.

⁴<https://bitbucket.org/neurorehablab/kave>

Components	KAVE	GIVA	CryVE	TIVS
Projection	4 Optoma GT1080 at 1920X1080 resolution	3 NEC-U310W at 1280X800 resolution	5 Hitachi ED-A100 at 1024x768 resolution	4 BenQ MW821ST at 1280x800 resolution
Tracking System	1 Kinect V2	6 optical cameras + VR glasses	No tracking	6 Flex:C120 infrared cameras + VR glasses
CAVE software	KAVE Plugin + Unity	WordViz Vizard + PPT software	CryVE + CryEngine	MiddleVR + Unity
Calibration	KAVECAM	N/A (assumed to be manual)	CryVR middleware	MiddleVR
Clustering Architecture	No	No	1 PC per projector clustered	No
Wall surfaces	2.8m x 2.1m (Left, Front, Right) + 2.1m x 2.1m Floor	3.0m x 2.7m (Projection 3,12m x 1,92m)	3.0m x 3.0m	1.8m x 2.2m

FIGURE 3.13: Taxonomy table of proposed solution and 3 other CAVEs

It's worthy to mention that each of the CAVEs presented above have their strong and weak points and choice of components is based on what the CAVE needs to accomplish. For example *Wall surfaces* is hard to compare since it's a design choice based on the CAVE owner but other components can be compared. Recapitulating:

- **KAVE** (developed in **2017**) is a multi-purpose CAVE that can run a wide variety of applications in various fields.
- **GIVA** (developed in **2014**) is a multi-user CAVE that main objective is to provide a system for geographical navigation.
- **CryVE CAVE** (developed in **2009**) objective is to provide a system that can handle high-graphical fidelity applications developed in CryEngine2.
- **TIVS** (developed in **2015**) main objective is to have an easily deployed CAVE focused on providing a VR experience in spaces where normal CAVEs are not an option.

Another point that is worthy to mention for this discussion is that we must take into consideration that these CAVEs were developed in different years and prices and accessibility of components fluctuate.

Clearly from the table above, the KAVE possess the highest display resolution out of the all the CAVEs in the table. In common sense, we perceive a system with more display resolution a better system compared to another. While this is true, there are performance implications that may affect decision making when building a CAVE system. For example CryVE CAVE was made with the purpose of presenting a CAVE for high graphical fidelity applications made in CryEngine2. One may think that having very high resolution in this system is a requirement (and it's correctly assumed) but high resolution also has impact in performance. Their decision of having lower resolution and clustered architecture probably has the objective of increasing the performance (one measure is FPS) of these computational demanding applications. However, in their paper[26] they reported low FPS (average of 19) with a single PC and FPS averaging 18 when the full cluster was in operation (the clustering also presented synchronization problems, introduced lag and complexity in assembling and maintenance). KAVE, on the other hand, when running the virtual environments used for the presence study of this thesis, clocked at 25 FPS on average with a much higher display resolution. GIVA and TIVS, while the focus is not to run visual stunning applications could have benefit from higher resolution setup presented in KAVE.

In terms of tracking, the GIVA and TIVS have a more precise method of tracking since they several optical cameras each and the KAVE uses a single Kinect. While the KAVE tracking system has less precision and more jittering than GIVA and TIVS, the cost of the tracking system present in the KAVE is much lower and extensible to use the user's body for interaction (and not just the head like GIVA and TIVS).

Regarding the CAVE software, KAVE, CryVE and TIVS are based on game engines applications which make them more optimized and consistent. GIVA only runs geographical applications so we could argue that the system is also consistent (but limited when running other applications). KAVE and CryVE use software developed in-house so their costs are pretty cheap when compared to GIVA and TIVS that use commercial software solution which are expensive. Something to note is that KAVE and TIVS are based on the same

game engine (Unity) but TIVS, like mentioned above, uses expensive commercial software so the KAVECAM and KAVE plugin for Unity presented in this paper could be an interesting alternative cost-wise to MiddleVR used in TIVS.

In terms of structure it's worth mentioning that KAVE structure allows adjustments in terms of projectors position and orientation to get the maximum out of the system's software calibration(KaveCAM).

The next figure 4.3 presents a comparison of CAVE costs in Euros.

Components	KAVE	GIVA	CryVE	TIVS
Projection	3200	4200	4100	3400
Tracking System	200	5100	0	3000
Structure and walls	1500	N/A	10600	900
Workstation	1200	2300	4600	1100
Total costs	6100€	11600€*	19300€	8400€

FIGURE 3.14: Comparison of costs of proposed solution and other 3 CAVEs (* - Cost was roughly estimated based on the specs available on their site description)

Prices from CryVE and TIVS were taken from their respective papers[26][29] and the prices for the GIVA were roughly estimated from the equipment described in their website.

As we can see in fig 4.3, KAVE possesses lower costs in every category and combination with the exception of *Structure and Walls* and *Workstation* when compared to the TIVS CAVE. KAVE possesses better projection equipment with higher resolution than any other with much lower cost. The tracking system is a bit less accurate like described above but the reduction in costs when compared to other CAVEs is far less which makes it an attractive solution.

Section conclusions Now that we've seen our proposed low-cost CAVE solution in terms of structure as well as its component including software and calibration process, in the next section we evaluate this CAVE in terms of presence as defined in section [2.7.1](#)

Chapter 4

Evaluation of KAVE

We have looked at our proposed solution of a low-cost CAVE in the previous section, however in this section we described the methods we used to evaluate it and compare to other ways of delivering VR technology. To achieve this, an experiment was conducted with voluntary participants not only to access KAVE in terms of presence, but also to compare it to a PC monitor as well as a Head-Mounted Display using the same techniques used to access the KAVE.

4.1 Study definition

The main purpose of this study is to evaluate the KAVE in terms of presence, when compared to other VR technologies, namely a simple PC display screen and the HTC VIVE. The main questions we aim this study to shed light into are:

- How does the KAVE compare in terms of presence to a PC and a Head Mounted Display?
- Which factors affect more the presence of a VR system in this context?
- Is it easier to perform tasks in the CAVE compared to PC and VIVE?

According to various reports found in the literature[43][44][45], CAVE systems are more presence inducing than HMDs but ahead of several other VR technologies like the PC for instance, but these reports are quite dated and facing the recent advancements in HMD technology, our assumption is that KAVE is going to score between the PC screen and the HMD. However, studying how far is the KAVE compared to HMD and which factors contribute the most or the least in both technologies allows us to, in the future, to narrow the gap as was done with the cost and accessibility.

To establish a fair basis of comparison in terms of presence the study doesn't include any interaction with a virtual world. This could possibly bias the results since the different systems use different interaction methods.

To assess the workload of the system we also prepared a simple task that will be further explained below.

4.2 Study methodology

4.2.1 Sample

For this study, 20 naive participants were recruited with ages greater than 18 years ($\bar{x} = 23$, $\sigma = 1.71$). While 15 of them were from Informatics Engineering they had no prior experience with VR technologies. They had, however, experience using the PC but this prior experience was not detrimental to the objectives of this study. All 20 of them were university students. While studying the effects of having prior experience with VR versus no experience in determining the effectiveness in VR training is interesting, this study does not encompass that and therefore, no sociodemographic variables were included.

4.2.2 Instrumentation

In this subsection we will describe all the instruments that were used in this study

4.2.2.1 CAVE

The KAVE consists of a conventional four-all CAVE architecture (three vertical walls and floor), four Optoma GT1080 projectors (1080p resolution), a Microsoft Kinect 2 to track the user's head position required for the parallax effect that the KAVE produces fixed in the middle of the front wall. This position covers most of the KAVE space and is the best suited place to increase the tracking effectiveness. Since four 1080p displays are quite demanding for a single computer node, a really good graphics card was used (Radeon R9 390 8GB) through a Multi Stream Transport (MST) hub. The particularity of this CAVE setup, besides being low-cost, is that no wearable sensors were used, like tracking shutter glasses or interaction wands typically found in similar CAVE setups.

4.2.2.2 Virtual Environments

To assess the CAVE, we developed three virtual environments in Unity:

- Beach Environment

This virtual environment depicts a tropical beach in which the user is standing near a pier with views over the encroaching seas as well as flora typically encountered in these islands. To achieve a believable experience focus was put into the water dynamics as well as the atmospherics, namely a sun rising to cause impact on the user. The idea of this environment is to have a stationary outdoor environment with minimal assets to introduce naive users to the technology and set expectations of said technology.



FIGURE 4.1: Beach virtual environment

- Moving Boat Environment

In this virtual environment the user is aboard a ship that is moving along a river. The boat travels along a fixed path with the duration of 30 seconds. The idea of this environment is to have movement, but due to the restricted interaction space designed for this study (2.8 meters long by 2.8 meters wide), the movement was introduced through this boat so users have a feeling

of traveling over greater distances. This environment also include apples, 4 being along the banks of the rivers and 2 inside the boat.

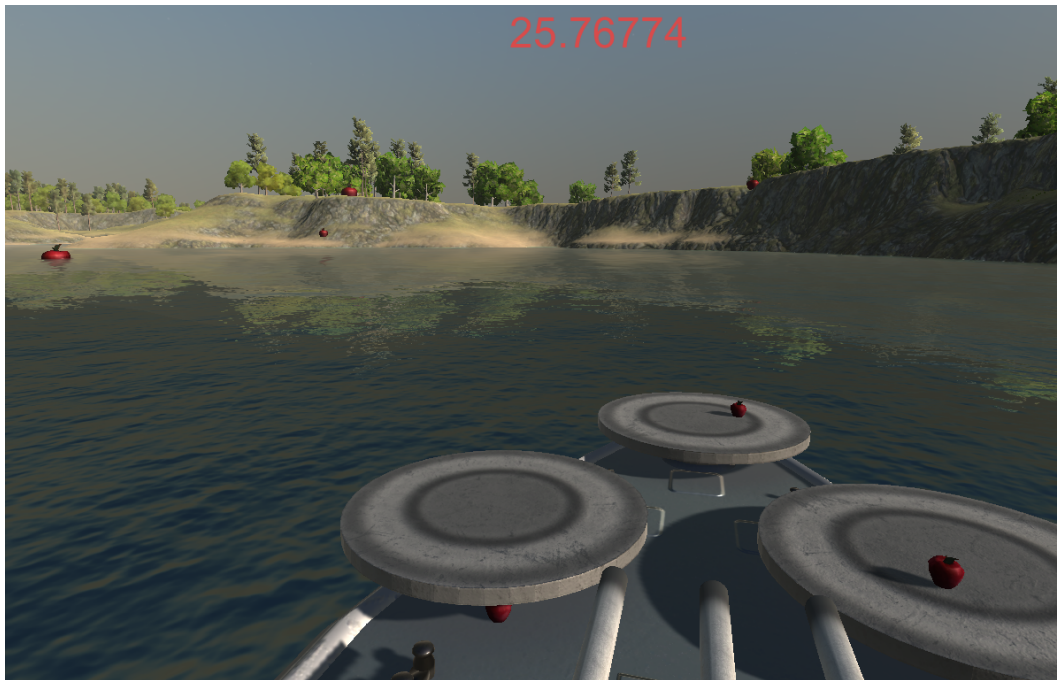


FIGURE 4.2: Depiction of the boat and the apples that the users are supposed to count in Moving Boat Environment

- House Environment

In this virtual environment the user is inside a modern house with lot of assets and lights. The rationale behind this environment is have a high graphical fidelity close environment. This environment also includes 10 apples scattered along the room and in combination with the higher of assets, provides an environment to place the apples in a way that makes most use of motion parallax.



FIGURE 4.3: VE3 is the highest graphical fidelity environment of all of the three scenes

All environments use Unity assets and were assembled in Unity 5.5. Users were not represented in avatar form in any of the environments.

Task The apples in the Moving Boat Environment and House Environment were used in the task that users had to perform to assess workload of the system. Users simply had to count how many apples they found. The fact that there was a single apple in the Beach Environment, 8 in the Moving Boat Environment and 10 in the House Environment, is to provide a ramp in difficulty as their comfort with the technology increases as well as to have more data about different aspects of the system (such as immersion parameters). The single apple in the Beach Environment was not registered. Since this VE(Beach Environment) is to introduce the users to the technology, the apple's only purpose was to give the user a visual cue of the type of object to look for in the other VEs (Moving Boat Environment and House Environment).

4.2.3 Procedure

The experiment was conducted by a single person who managed all of the modalities and provided safety and guidance to the participants. Before

each experimental sessions, the participants were explained about what they were allowed to do in each VE and about what to do. In the Beach Environment experiment they had freedom to navigate the interaction space and they had no task to perform. In the Moving Boat Environment and the House Environment they had to watch out for the apples and count them.

To avoid technology bias, the order of the conditions (in other words, if they started with PC, CAVE or VIVE) was randomized. In the PC condition, users navigated the interaction space using keyboard to move and mouse to look around. In CAVE and HMD conditions they used the body to move in the interaction space.

In each condition, participants went through the three VE's consecutively with no downtime, with the duration of 30 seconds in each VE (a timer was put on screen to alert users when the VE would change to the next one).

After each condition, participants rated the presence of the system using the original Slater-Usuh-Steed Questionnaire and a modified version of the Presence Questionnaire (presented in [46] while preparations were made for them to take the next condition. The Slater-Usuh-Steed Questionnaire consists of six item rated on a seven point Likert scale that assesses presence as a concept of transportation and the modified Presence Questionnaire[46] by Witmer that consists in 21 items rated also on a seven point Likert scale, assessing presence as a concept of immersion and as a concept of realism, divided in 5 factors - visual aspects, interaction, consistency with the real world and other subjective factors scoring from 21 to 140.

To add to both questionnaires about presence, users also rated the workload of each system using the modified NASA TLX questionnaire. Modified in the sense that the original NASA TLX is a two-part test. The first part consist of the total workload of the system divided in six subscales scoring from 0 to 100 points with twenty 5-point steps. The six subscales are the following:

- Mental Demand
- Physical Demand
- Temporal Demand
- Performance

- Effort
- Frustration

The second part has the users weight each of the factors present in the NASA TLX that they found most relevant according to their experience and these weights are multiplied by each of the sub-scales to provide a total score. Our approach dropped the individual weighting and used only the first part of the NASA TLX (also known as Raw TLX) since there has been evidence supporting this shortened version over the full one since it might increase validity.[47]

All three questionnaires used are available in the Appendix, at the end of this thesis.

The following diagram depicts the study procedure described in the previous paragraphs.

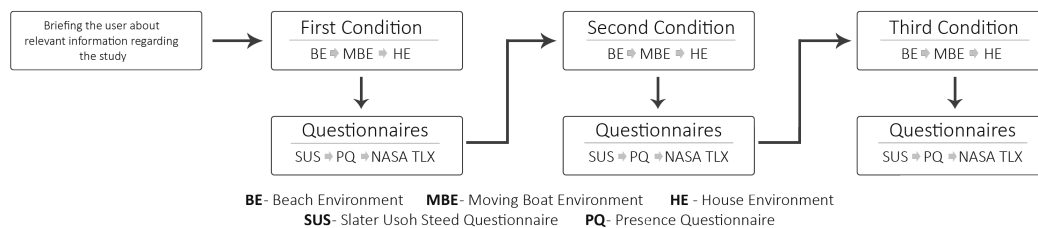


FIGURE 4.4: Diagram depicting the study procedure. Conditions are PC, CAVE and VIVE.

The data collection that happened over a period of 7 days, the data was inputted in statistical analysis software *Statistical Package for the Social Science* (SPSS - version 24.0).

4.3 Study results

In this section we go over the results obtained in this study. Firstly, we proceeded to the execution of descriptive statistics (minimum, maximum, averages and standard deviations). To check if the results were statistically meaningful we used the Wilcoxon paired test since this test is appropriate for analyzing data from a repeated-measures design with in which the same participants performed all conditions. The use of the Wilcoxon test is further corroborated by the sample size being less than 30 (20 participants and

the data obtained through the questionnaires being measured on an ordinal scale). This test is a non-parametric version of the t-test Student.

The logic behind Wilcoxon is easily explained: This test is applied to a pair of conditions to produce two rank totals, one positive and one negative. If there is a systematic difference between both conditions then most of the high ranks will be in one of the sides (positive or negative) while most of the low ranks will belong to the other. This is the ideal case where there is statistically significance between two conditions. If two conditions are similar, the number of ranks in each side (positive or negative) will also be similar. This wilcoxon test produces a value "W" which is simply the smaller of the rank totals. The smaller this value is, the less likely it is that the event occurred by pure chance. If the W value is smaller than the critical value (in this study we use a two tailed significance level of 0.05) then we can say that this didn't occurred by chance and extrapolate the sample data to the population data.

4.3.1 Slater-Usch-Steed Questionnaire

The next figures show results for the SUS questionnaire. It's important to remind that the SUS questionnaire assesses the conceptualization of presence as transportation of a Virtual Reality technology in a scoring system ranging from 7 to 35.

	N	Mean	Std. Deviation	Minimum	Maximum	Percentiles		
						25th	50th (Median)	75th
PC	20	15,30	5,564	9	27	11,00	13,00	17,00
CAVE	20	22,5500	3,42552	17,00	29,00	20,2500	23,0000	24,7500
VIVE	20	25,7500	2,14905	21,00	29,00	24,0000	26,0000	27,7500

FIGURE 4.5: Slater-Usch-Steed questionnaire descriptive statistics summarized

The table above illustrates that the VIVE scored the highest in the SUS questionnaire and the PC scored the lowest, with the CAVE scoring in between PC and VIVE. Also, both CAVE and VIVE had particularly small spreads ($\sigma = 3.42552$ and $\sigma = 2.14985$ respectively).

SUS Questionnaire - Signed Ranks

		N	Mean Rank	Sum of Ranks
PC - CAVE	Negative Ranks	1 ^a	3,50	3,50
	Positive Ranks	19 ^b	10,87	206,50
	Ties	0 ^c		
	Total	20		
CAVE - VIVE	Negative Ranks	0 ^d	,00	,00
	Positive Ranks	17 ^e	9,00	153,00
	Ties	3 ^f		
	Total	20		

a. SUS_CAVE_TOTAL < SUS_PC_TOTAL
b. SUS_CAVE_TOTAL > SUS_PC_TOTAL
c. SUS_CAVE_TOTAL = SUS_PC_TOTAL
d. SUS_VIVE_TOTAL < SUS_CAVE_TOTAL
e. SUS_VIVE_TOTAL > SUS_CAVE_TOTAL
f. SUS_VIVE_TOTAL = SUS_CAVE_TOTAL

FIGURE 4.6: SUS Signed Ranks

The table above illustrates the signed ranks of the Wilcoxon test for the SUS questionnaire. Both pairs obtained large discrepancies in ranks - the pair PC-CAVE obtained 1 negative rank and 19 positive and the pair CAVE-VIVE obtained 0 negative ranks, 17 positive ranks and 3 ties. This is reflected in the sum of each signed ranks with both pairs having large one-sided (in this case positive) ranks.

SUS - Wilcoxon Test

	PC - CAVE	CAVE - VIVE
Z	-3,795	-3,632
Asymp. Sig. (2-tailed)	,000	,000

FIGURE 4.7: SUS Wilcoxon Values

Concluding the results for the SUS questionnaire, the table above shows that both pairs obtained a value lower than the critical value of 0.05, with Z (difference of means) being similar in both cases.

4.3.2 Presence Questionnaire

Next, let's look at how the three technologies behaved when put against the PQ (Presence Questionnaire). Again, it is important to remind that the Presence Questionnaire scores vary from 21 to 147 points, divided into four factors:

- Visual Aspects (scaled from 1 to 49 points)
- Interaction (scaled from 1 to 42)
- Consistency with the real world (scaled from 1 to 21)
- Subjective factors (scaled from 1 to 35)

Below, we presents the results in each of the aforementioned four domains.

4.3.2.1 PQ - Visual Aspects

	N	Mean	Std. Deviation	Minimum	Maximum	Percentiles		
						25th	50th (Median)	75th
PC	20	27,50	5,530	18	43	24,25	27,50	30,00
CAVE	20	32,5500	6,15993	21,00	43,00	29,0000	33,0000	37,7500
VIVE	20	38,1000	4,54104	27,00	45,00	37,0000	39,0000	41,0000

FIGURE 4.8: Visual Aspects domain descriptive statistics

In the table above we note that VIVE scored the highest in terms of the Visual Aspects domain ($\bar{x} = 38.1$) while the PC scored the lowest ($\bar{x} = 27.50$). Also, the CAVE had the highest spread of data ($\sigma = 6,15993$). We recurred to the Wilcoxon paired test to check if the averages are statistically significant with a critical value of 0.05 ($p = 0.05$). The table below sums the negative and positive ranks of this domain.

PQ VA - Wilcoxon Signed Ranks

		N	Mean Rank	Sum of Ranks
PC-CAVE	Negative Ranks	4 ^a	9,38	37,50
	Positive Ranks	16 ^b	10,78	172,50
	Ties	0 ^c		
	Total	20		
CAVE-VIVE	Negative Ranks	5 ^d	4,60	23,00
	Positive Ranks	15 ^e	12,47	187,00
	Ties	0 ^f		
	Total	20		

- a. PQ_CAVE_VA < PQ_PC_VA
 b. PQ_CAVE_VA > PQ_PC_VA
 c. PQ_CAVE_VA = PQ_PC_VA
 d. PQ_VIVE_VA < PQ_CAVE_VA
 e. PQ_VIVE_VA > PQ_CAVE_VA
 f. PQ_VIVE_VA = PQ_CAVE_VA

FIGURE 4.9: Visual Aspects domain Signed Ranks

The pair PC-CAVE had no ties, with 4 negative ranks and 16 positive ranks. On the other hand the pair CAVE-VIVE also had no ties, with 5 negative ranks and 15 positive ranks. The discrepancy of the sum of the ranks was higher in the pair CAVE-VIVE. This tentative data preliminary indicates at least that the difference is higher in the pair CAVE-VIVE than in the pair PC-CAVE but to check if this different is statistically significant, the table below shows the value obtained in the Wilcoxon test in this domain.

PQ VA - Wilcoxon Test

	PC-CAVE	CAVE-VIVE
Z	-2,522	-3,067
Asymp. Sig. (2-tailed)	,012	,002

FIGURE 4.10: Visual Aspects domain Wilcoxon values

The table above shows that the pair PC-CAVE obtained a W value of 0.012, lower than the critical value and the pair CAVE-VIVE obtained a value of 0.002.

4.3.2.2 PQ - Interaction

Presence Questionnaire Interaction - Descriptive Statistics

	N	Mean	Std. Deviation	Minimum	Maximum	Percentiles		
						25th	50th (Median)	75th
PC	20	21,3500	6,24310	12,00	34,00	17,0000	21,0000	26,0000
CAVE	20	28,5000	4,45445	22,00	37,00	24,2500	28,5000	30,7500
VIVE	20	30,8000	3,87434	22,00	35,00	28,2500	31,5000	35,0000

FIGURE 4.11: Interaction descriptive statistics

In the interaction domain, VIVE scored higher while the PC scored the lowest of the three. The PC also had the highest spread ($\sigma = 6.24310$).

PQ INT - Wilcoxon Signed Ranks

		N	Mean Rank	Sum of Ranks
PC - CAVE	Negative Ranks	3 ^a	5,50	16,50
	Positive Ranks	16 ^b	10,84	173,50
	Ties	1 ^c		
	Total	20		
CAVE - VIVE	Negative Ranks	6 ^d	7,00	42,00
	Positive Ranks	12 ^e	10,75	129,00
	Ties	2 ^f		
	Total	20		

a. PQ_CAVE_INT < PQ_PC_INT
b. PQ_CAVE_INT > PQ_PC_INT
c. PQ_CAVE_INT = PQ_PC_INT
d. PQ_VIVE_INT < PQ_CAVE_INT
e. PQ_VIVE_INT > PQ_CAVE_INT
f. PQ_VIVE_INT = PQ_CAVE_INT

FIGURE 4.12: Interaction domain Signed Ranks

In the Wilcoxon Signed ranks, the discrepancy between the negative ranks and positive ranks was higher in the pair PC-CAVE than in the pair CAVE-VIVE, with the CAVE being closer to the VIVE in terms of the interaction domain.

	PC - CAVE	CAVE - VIVE
Z	-3,162	-1,901
Asymp. Sig. (2-tailed)	,002	,057

FIGURE 4.13: Interaction domain Wilcoxon values

The table above shows that the pair PC-CAVE obtained a value of 0.002 (lower than the critical value of 0.05) and the pair CAVE-VIVE obtained a value of 0.057 (higher than the critical value of 0.05). The Z value (difference of means) was higher in the pair PC-CAVE when compared to the pair CAVE-VIVE.

4.3.2.3 PQ - Consistency with the real world

	N	Mean	Std. Deviation	Minimum	Maximum	Percentiles		
						25th	50th (Median)	75th
PQ_PC_CONS	20	15,0000	3,30868	7,00	20,00	12,2500	15,0000	17,0000
PQ_CAVE_CONS	20	15,1000	3,61139	7,00	20,00	12,0000	16,0000	18,0000
PQ_VIVE_CONS	20	17,6500	2,34577	13,00	21,00	15,5000	17,5000	19,7500

FIGURE 4.14: Consistency with the real world domain descriptive statistics

Regarding the consistency with the real world, again the VIVE scored the highest with CAVE and the PC scoring closely averages.

PQ CONS - Wilcoxon Signed Ranks

		N	Mean Rank	Sum of Ranks
PC - CAVE	Negative Ranks	8 ^a	8,50	68,00
	Positive Ranks	8 ^b	8,50	68,00
	Ties	4 ^c		
	Total	20		
CAVE - VIVE	Negative Ranks	3 ^d	4,00	12,00
	Positive Ranks	17 ^e	11,65	198,00
	Ties	0 ^f		
	Total	20		

a. PQ_CAVE_CONS < PQ_PC_CONS
b. PQ_CAVE_CONS > PQ_PC_CONS
c. PQ_CAVE_CONS = PQ_PC_CONS
d. PQ_VIVE_CONS < PQ_CAVE_CONS
e. PQ_VIVE_CONS > PQ_CAVE_CONS
f. PQ_VIVE_CONS = PQ_CAVE_CONS

FIGURE 4.15: Consistency with the real world domain Signed Ranks

In fact, the similar means of PC and CAVE is reflected well in the Signed Ranks table above with the pair PC CAVE obtaining the same number of positive and negative ranks (8 positive and 8 negative) with 4 ties. The sum of positive and negative ranks was also identical (68). On the other hand, the pair CAVE-VIVE obtained a large discrepancy in the sum of positive ranks and the sum of negative ranks.

PQ CONS - Wilcoxon Test

	PC - CAVE	CAVE - VIVE
Z	,000	-3,498
Asymp. Sig. (2-tailed)	1,000	,000

FIGURE 4.16: Consistency with the real world domain Wilcoxon values

The final result of Wilcoxon test for this domain (presented in the table

above) was, for the pair PC-CAVE, a value of 1.000 (a lot higher than the critical value of 0.05) with a mean difference of 0.000, while the CAVE-VIVE had a value 0.000(inferior than the critical value of 0.05) and a mean difference of -3.498)

4.3.2.4 PQ - Subjective factors

Presence Questionnaire Subjective Factors - Descriptive Statistics

	N	Mean	Std. Deviation	Minimum	Maximum	Percentiles		
						25th	50th (Median)	75th
PC	20	22,3500	5,68724	13,00	34,00	18,0000	24,0000	25,0000
CAVE	20	24,3500	5,47025	14,00	32,00	19,2500	25,0000	29,0000
VIVE	20	27,0000	4,48389	17,00	33,00	26,0000	28,0000	30,0000

FIGURE 4.17: Subjective factors domain descriptive statistics

Regarding the subjective factors domain of the Presence questionnaire the VIVE scored the highest while the PC scored the lowest. In the PC we also found the highest spread($\sigma = 5.69726$), with the CAVE obtaining a similar spread ($\sigma = 5.47825$).

PQ SUBJEC - Wilcoxon Signed Ranks

		N	Mean Rank	Sum of Ranks
PC - CAVE	Negative Ranks	5 ^a	11,00	55,00
	Positive Ranks	14 ^b	9,64	135,00
	Ties	1 ^c		
	Total	20		
CAVE - VIVE	Negative Ranks	4 ^d	8,13	32,50
	Positive Ranks	13 ^e	9,27	120,50
	Ties	3 ^f		
	Total	20		

a. PQ_CAVE_SUBJEC < PQ_PC_SUBJEC

b. PQ_CAVE_SUBJEC > PQ_PC_SUBJEC

c. PQ_CAVE_SUBJEC = PQ_PC_SUBJEC

d. PQ_VIVE_SUBJEC < PQ_CAVE_SUBJEC

e. PQ_VIVE_SUBJEC > PQ_CAVE_SUBJEC

f. PQ_VIVE_SUBJEC = PQ_CAVE_SUBJEC

FIGURE 4.18: Subjective factors domain Signed Ranks

The discrepancy of the sum of negative ranks and the sum of positive ranks was similar in both pairs with the pair CAVE-VIVE having higher discrepancy.

PQ SUBJECT - Wilcoxon Test

	PC - CAVE	CAVE - VIVE
Z	-1,614	-2,087
Asymp. Sig. (2-tailed)	,106	,037

FIGURE 4.19: Subjective factors domain Wilcoxon values

Although the discrepancies in the sum of ranks was similar, since the pair CAVE-VIVE had 3 ties (compared to only 1 tie in the pair PC-CAVE), this translated in the PC-CAVE pair having a value (0.106) higher than the critical value and the pair CAVE-VIVE having a value (0.037) lower than the critical value.

4.3.3 Raw NASA TLX

In this subsection we present the data obtained through the use of Raw version of NASA TLX. As a reminder, this questionnaire is different from both questionnaires presented above since it doesn't assess presence but workload of a system instead. Like previously mentioned, this test is divided in six domains - Mental Demand, Physical Demand, Temporal Demand, Performance, Effort and Frustration. Each of this domains is assessed in a scale of 0 to 100 points where the closer to 0 the score is, the better it is in the respective domain.

4.3.3.1 Mental Demand

This domain is assessed in the RAW NASA TLX through the following question:

- How mentally demanding was the task?

	N	Mean	Std. Deviation	Minimum	Maximum	Percentiles		
						25th	50th (Median)	75th
PC Mental Demand	20	32,00	19,494	10	75	15,00	32,50	38,75
CAVE Mental Demand	20	25,75	12,594	5	60	16,25	25,00	30,00
VIVE Mental Demand	20	27,00	10,930	15	60	20,00	25,00	30,00

FIGURE 4.20: Mental Demand domain descriptive statistics

In this domain, the CAVE scored the best (lowest average of 25,74) while the PC scored the worst while having the highest spread of data.

		N	Mean Rank	Sum of Ranks
PC - CAVE	Negative Ranks	14 ^a	10,18	142,50
	Positive Ranks	6 ^b	11,25	67,50
	Ties	0 ^c		
	Total	20		
CAVE - VIVE	Negative Ranks	7 ^d	8,00	56,00
	Positive Ranks	9 ^e	8,89	80,00
	Ties	4 ^f		
	Total	20		

- a. CAVE Mental Demand < PC Mental Demand
 b. CAVE Mental Demand > PC Mental Demand
 c. CAVE Mental Demand = PC Mental Demand
 d. VIVE Mental Demand < CAVE Mental Demand
 e. VIVE Mental Demand > CAVE Mental Demand
 f. VIVE Mental Demand = CAVE Mental Demand

FIGURE 4.21: Mental Demand domain Signed Ranks

The discrepancy of the sum of negative ranks and the sum of positive ranks was higher in the pair CAVE- VIVE than in the pair PC-CAVE. Special notice to the similar number of ranks in both signs in the CAVE-VIVE pair and respective 4 ties.

	PC-CAVE	CAVE-VIVE
Z	-1,407	-,625
Asymp. Sig. (2-tailed)	,159	,532

FIGURE 4.22: Mental Demand domain Wilcoxon values

While the signed ranks table potentially indicates differences, the Wilcoxon values in both pairs were above the critical value of 0.05 ($W[\text{PC-CAVE}] = 0.159$, $W[\text{CAVE-VIVE}] = .532$)

4.3.3.2 Physical Demand

This domain is assessed in the RAW NASA TLX through the following question:

- How physically demanding was the task?

	N	Mean	Std. Deviation	Minimum	Maximum	Percentiles		
						25th	50th (Median)	75th
PC Physical Demand	20	19,50	11,687	5	45	10,00	17,50	28,75
CAVE Physical Demand	20	29,50	16,929	5	55	20,00	20,00	52,50
VIVE Physical Demand	20	30,25	16,016	15	70	20,00	25,00	38,75

FIGURE 4.23: Physical Demand domain descriptive statistics

In this domain, the PC scored the best in terms of physical demand with an average of 19.50 points (scale of 0 to 100 points) while VIVE proved to be the worst score with an average of 30.50 points. The PC data also showed the least spread among the three technologies

Physical Demand Signed Ranks

		N	Mean Rank	Sum of Ranks
PC - CAVE	Negative Ranks	4 ^a	7,50	30,00
	Positive Ranks	14 ^b	10,07	141,00
	Ties	2 ^c		
	Total	20		
CAVE - VIVE	Negative Ranks	9 ^d	8,89	80,00
	Positive Ranks	8 ^e	9,13	73,00
	Ties	3 ^f		
	Total	20		

- a. CAVE Physical Demand < PC Physical Demand
 b. CAVE Physical Demand > PC Physical Demand
 c. CAVE Physical Demand = PC Physical Demand
 d. VIVE Physical Demand < CAVE Physical Demand
 e. VIVE Physical Demand > CAVE Physical Demand
 f. VIVE Physical Demand = CAVE Physical Demand

FIGURE 4.24: Physical Demand domain Signed Ranks

In terms of signed ranks the pair CAVE-VIVE showed similarities with 9 negative ranks to 8 positive ranks and 3 ties while the pair PC-CAVE shows a much higher discrepancy of 4 negative ranks to 14 positive ranks and 2 ties.

Physical Demand Wilcoxon Values

	PC - CAVE	CAVE - VIVE
Z	-2,439	-,166
Asymp. Sig. (2-tailed)	,015	,868

FIGURE 4.25: Physical Demand domain Wilcoxon values

In this domain the pair PC-CAVE presents a W value of 0.015 (lower than the critical value of 0.05) and the pair CAVE-VIVE a W value of 0.868 (much higher than the critical value of 0.05)

4.3.3.3 Temporal Demand

This domain is assessed in the RAW NASA TLX through the following question:

- How hurried or rushed was the pace of the task?

	N	Mean	Std. Deviation	Minimum	Maximum	Percentiles		
						25th	50th (Median)	75th
PC Temporal Demand	20	33,00	18,310	5	70	20,00	32,50	43,75
CAVE Temporal Demand	20	29,50	15,969	10	75	20,00	25,00	35,00
VIVE Temporal Demand	20	28,25	17,035	10	80	20,00	22,50	32,50

FIGURE 4.26: Temporal Demand domain descriptive statistics

In terms of the Temporal Demand domain, VIVE scored the best ($\bar{x} = 28.25$ points) while the PC scored the worst. ($\bar{x} = 33.00$). The spreads were lower in the CAVE while the highest in the PC

		N	Mean Rank	Sum of Ranks
PC - CAVE	Negative Ranks	11 ^a	8,73	96,00
	Positive Ranks	6 ^b	9,50	57,00
	Ties	3 ^c		
	Total	20		
CAVE - VIVE	Negative Ranks	7 ^d	7,21	50,50
	Positive Ranks	6 ^e	6,75	40,50
	Ties	7 ^f		
	Total	20		

a. CAVE Temporal Demand < PC Temporal Demand

b. CAVE Temporal Demand > PC Temporal Demand

c. CAVE Temporal Demand = PC Temporal Demand

d. VIVE Temporal Demand < CAVE Temporal Demand

e. VIVE Temporal Demand > CAVE Temporal Demand

f. VIVE Temporal Demand = CAVE Temporal Demand

FIGURE 4.27: Temporal Demand domain Signed Ranks

Also in this domain, the pair CAVE-VIVE shows to be similar in signed ranks ratio (7 positive to 6 negative and 7 ties) while the pair PC-CAVE 11

negative ranks to 6 positive ranks and 3 ties, concluding that the discrepancy was higher in the PC-CAVE pair than in the CAVE-VIVE pair.

	PC - CAVE	CAVE - VIVE
Z	-,932	-,354
Asymp. Sig. (2-tailed)	,351	,723

FIGURE 4.28: Temporal Demand domain Wilcoxon values

Again, both pairs obtained a W value higher than the critical value of 0.05. The pair PC-CAVE obtained a W value of 0.351 and the pair CAVE-VIVE 0.723.

4.3.3.4 Performance

This domain is assessed in the RAW NASA TLX through the following question:

- How successful were you in accomplishing what you were asked to do?

	N	Mean	Std. Deviation	Minimum	Maximum	Percentiles		
						25th	50th (Median)	75th
PC Performance	20	20,25	7,340	5	30	15,00	20,00	25,00
CAVE Performance	20	20,25	9,101	5	40	15,00	20,00	25,00
VIVE Performance	20	19,25	7,482	10	40	15,00	17,50	20,00

FIGURE 4.29: Performance domain descriptive statistics

Very similar data obtained in the three conditions (PC, CAVE, VIVE) with the VIVE scoring the best ($\bar{x} = 18.25$). PC and CAVE obtained the same average of 20.25 ($\bar{x} = 20.25$)

Performance Signed Ranks

		N	Mean Rank	Sum of Ranks
PC - CAVE	Negative Ranks	9 ^a	7,39	66,50
	Positive Ranks	7 ^b	9,93	69,50
	Ties	4 ^c		
	Total	20		
CAVE - VIVE	Negative Ranks	11 ^d	7,82	86,00
	Positive Ranks	6 ^e	11,17	67,00
	Ties	3 ^f		
	Total	20		

- a. CAVE Performance < PC Performance
 b. CAVE Performance > PC Performance
 c. CAVE Performance = PC Performance
 d. VIVE Performance < CAVE Performance
 e. VIVE Performance > CAVE Performance
 f. VIVE Performance = CAVE Performance

FIGURE 4.30: Performance domain Signed Ranks

Very similar ratio of positive ranks and negative ranks with similar ties also in both pairs. However the discrepancy of the sum of both ranks was higher in the CAVE-VIVE pair

Performance Wilcoxon Values

	PC - CAVE	CAVE - VIVE
Z	-,079	-,453
Asymp. Sig. (2-tailed)	,937	,650

FIGURE 4.31: Performance domain Wilcoxon values

Both pairs showed high W values with the PC-CAVE pair having a value of almost 1.000 ($W=0.937$) while the CAVE-VIVE pair obtaining a W value of 0.650. Both values are above the critical value of 0.05.

4.3.3.5 Effort

This domain is assessed in the RAW NASA TLX through the following question:

- How hard did you have to work to accomplish you level of performance?

	N	Mean	Std. Deviation	Minimum	Maximum	Percentiles		
						25th	50th (Median)	75th
PC Effort	20	23,00	15,594	5	75	16,25	20,00	25,00
CAVE Effort	20	29,75	23,140	5	80	15,00	20,00	43,75
VIVE Effort	20	23,00	19,695	5	85	10,00	15,00	23,75

FIGURE 4.32: Effort domain descriptive statistics

In this domain, the CAVE scored the worst in an average of 29.75 points while also having the highest spread of 23.140. Both PC and CAVE scored the same in terms of average points.

		N	Mean Rank	Sum of Ranks
PC - CAVE	Negative Ranks	7 ^a	6,21	43,50
	Positive Ranks	8 ^b	9,56	76,50
	Ties	5 ^c		
	Total	20		
CAVE - VIVE	Negative Ranks	10 ^d	11,50	115,00
	Positive Ranks	8 ^e	7,00	56,00
	Ties	2 ^f		
	Total	20		

a. CAVE Effort < PC Effort

b. CAVE Effort > PC Effort

c. CAVE Effort = PC Effort

d. VIVE Effort < CAVE Effort

e. VIVE Effort > CAVE Effort

f. VIVE Effort = CAVE Effort

FIGURE 4.33: Effort domain Signed Ranks

In terms of negative and positive ranks, both pairs had quite similar ratios but since the pair PC-CAVE obtained 5 ties (to only 2 ties of the pair CAVE-VIVE), this translated in higher discrepancy in the pair CAVE-VIVE than in the pair PC-CAVE.

	PC - CAVE	CAVE - VIVE
Z	-,940	-1,296
Asymp. Sig. (2-tailed)	,347	,195

FIGURE 4.34: Effort domain Wilcoxon values

Following the trend of previous domains, both pairs scored higher than the critical value of 0.05 with the pair PC-CAVE obtaining a W value of 0.347 and the pair CAVE-VIVE obtaining a W value of 0.195.

4.3.3.6 Physical Demand

This domain is assessed in the RAW NASA TLX through the following question:

- How insecure, discouraged, irritated, stressed and annoyed were you?

	N	Mean	Std. Deviation	Minimum	Maximum	Percentiles		
						25th	50th (Median)	75th
PC Frustration	20	17,75	11,059	5	40	5,00	20,00	25,00
CAVE Frustration	20	17,25	16,341	5	55	5,00	10,00	20,00
VIVE Frustration	20	18,00	11,169	5	45	10,00	15,00	23,75

FIGURE 4.35: Frustration domain descriptive statistics

In terms of Frustration domain, the data between all three condition was similar in terms of average with both PC and CAVE obtaining the same average of 17.25 and VIVE obtaining an average of 18.00.

		N	Mean Rank	Sum of Ranks
PC - CAVE	Negative Ranks	8 ^a	7,13	57,00
	Positive Ranks	6 ^b	8,00	48,00
	Ties	6 ^c		
	Total	20		
CAVE - VIVE	Negative Ranks	6 ^d	8,83	53,00
	Positive Ranks	10 ^e	8,30	83,00
	Ties	4 ^f		
	Total	20		

a. CAVE Frustration < PC Frustration
b. CAVE Frustration > PC Frustration
c. CAVE Frustration = PC Frustration
d. VIVE Frustration < CAVE Frustration
e. VIVE Frustration > CAVE Frustration
f. VIVE Frustration = CAVE Frustration

FIGURE 4.36: Frustration domain Signed Ranks

In terms of signed ranks the pair PC-CAVE obtained 8 negative ranks, 6 positive ranks and 6 ties while the pair CAVE-VIVE obtained higher discrepancy with 6 negative ranks, 10 positive ranks and 4 ties. This is also shown by the difference of each Sum of Ranks being higher in the pair CAVE-VIVE.

	PC - CAVE	CAVE - VIVE
Z	-,283	-,781
Asymp. Sig. (2-tailed)	,777	,435

FIGURE 4.37: Frustration domain Wilcoxon values

Both pairs obtained a W value higher than the critical value of 0.05 with the pair PC-CAVE obtaining a W value of 0.777 and the pair CAVE-VIVE obtaining a W value of 0.435.

4.3.4 Results resumed

In this section we present the agglomeration of all three questionnaires and their respective domains for easy comprehension and digestion.

The following three graphs represent each questionnaire's results plotted by domain. The bold number above the intersections of two conditions indicate the significance level of the respective pair (Wilcoxon value). The Y-axis denotes the average and the X-axis denotes the conditions (if applied). Also, it's worthy to remind that contrary to most questionnaires, the NASA TLX scoring is reversed meaning that the lower the score is the better it is in their respective domain.

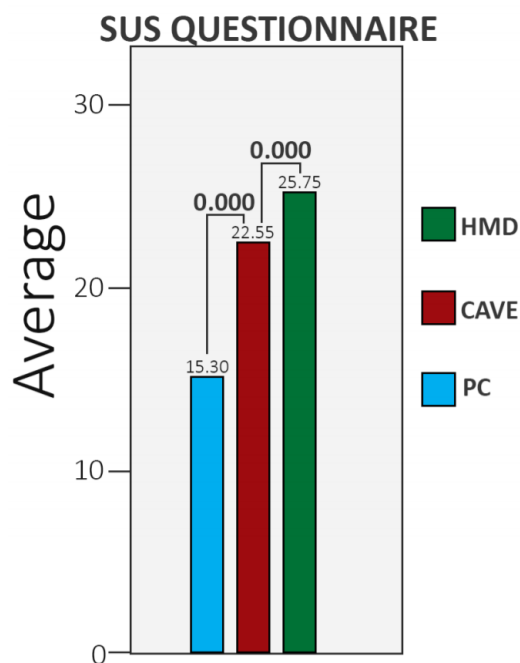


FIGURE 4.38: Summary SUS Plot

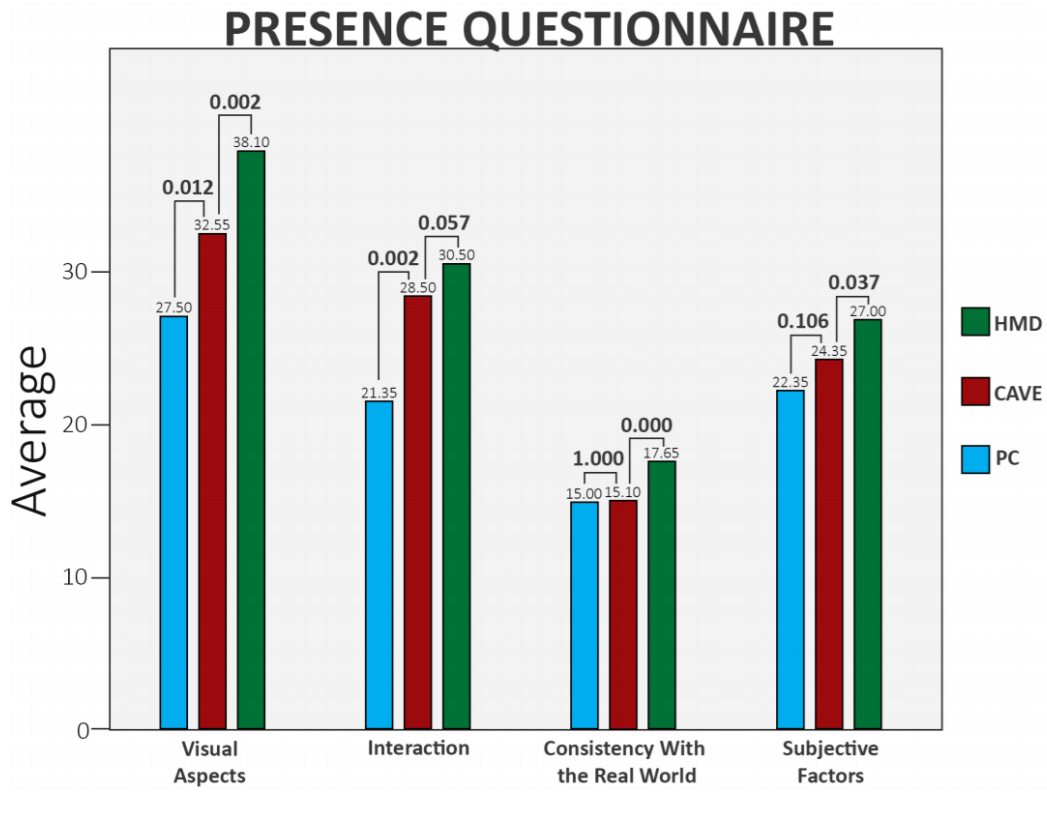


FIGURE 4.39: Summary PQ Plot

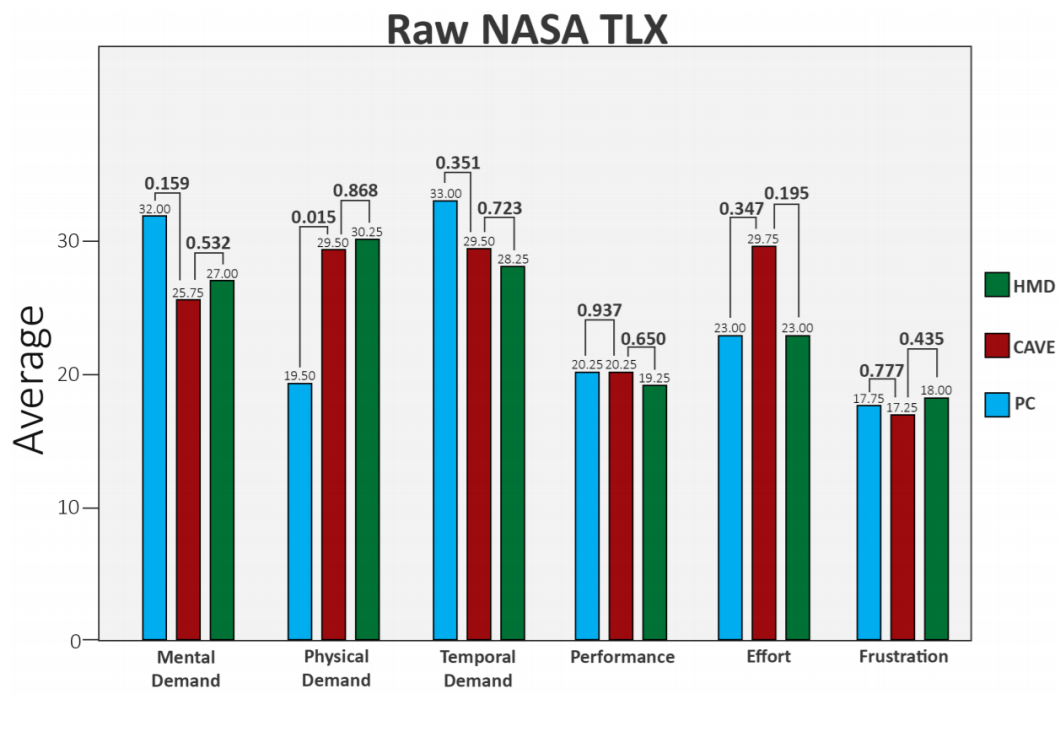


FIGURE 4.40: Summary NASA TLX Plot

The figure below shows the W values obtained from the Wilcoxon test in all three questionnaires and their respective domains. The boxes in dark gray represent that the W value contained in them is below the critical value of 0.05 and mean that there is statistically significant difference in the averages of pairs and the data produced in them was not obtained by pure chance.

	SUS	PQ				NASA TLX					
		VA	INT	CONS	SUBJECT	MD	PD	TD	P	E	F
PC - CAVE	0.000	0.012	0.002	1.000	0.106	0.159	0.015	0.351	0.937	0.347	0.777
CAVE - VIVE	0.000	0.002	0.057	0.000	0.037	0.532	0.868	0.723	0.650	0.195	0.435

Statistically not significant
 Statistically significant

FIGURE 4.41: Summary Wilcoxon table of all questionnaires and their respective domains applied to all conditions

The figure below shows the averages obtained in each domain of each questionnaire. Please note the values in square brackets denotes the scoring ranges of each domain.

	SUS	PQ				NASA TLX					
	[1-35]	[21-147]									
		VA	INT	CONS	SUBJECT	MD	PD	TD	P	E	F
		[1-49]	[1-42]	[1-21]	[1-35]	[0-100]	[0-100]	[0-100]	[0-100]	[0-100]	[0-100]
PC	15.30	27.50	21.35	15.00	22.35	32.00	19.50	33.00	20.25	23.00	17.75
CAVE	22.55	32.55	28.50	15.10	24.35	25.75	29.50	29.50	20.25	29.75	17.25
VIVE	25.75	38.10	30.50	17.65	27.00	27.00	30.25	28.25	19.25	23.00	18.00

FIGURE 4.42: Summary averages table of all questionnaires and their respective domains applied to all conditions

Chapter 5

Discussion

Similarly to the content exposed in the previous chapter, in the next section we supplement an analysis of the data and provide a discussion based in the literature and according to the study goals (see chapter 4.1)

5.1 Data discussion

To help shed some light in how the KAVE compares to both PC and HMD's let's start by looking at the overall totals of both presence questionnaires (SUS and Presence questionnaire). We notice that the CAVE is more presence inducing than the PC and less presence inducing than VIVE Head-Mounted display in all assessed conceptualizations of presence (SUS questionnaire mapping to the conceptualization of presence as transportation and PQ mapping to conceptualization of presence as immersion and conceptualization of presence as realism), contradicting some older papers[43][44][45] in the literature that report that CAVEs are more presence inducing than HMD. This may in fact be explained by the advancements in Head-Mounted display technologies in recent years in which our hypothesis that HMDs nowadays are more presence inducing than CAVEs was based on.

Given our hypothesis described in the last paragraph, these overall resulting scores aren't much of a surprise. What is rather surprising is the fact that the gap in these two systems was rather small in the SUS questionnaire. Our hypothesis was that the our custom-built CAVE was going to have a larger gap when put against a professional-grade Head-Mounted display but that data shows otherwise - The HMD VIVE scoring in average 25,75 points out of 35 equaling to approximately 74% of the maximum score and the KAVE scoring in average 22,55 out of 35 equaling a 65% maximum score. In last place in scoring terms came the PC which scored an average of 15,30 resulting in a 43

% of maximum score for the SUS questionnaire. Since the Wilcoxon showed that in the SUS questionnaire all the averages obtained are statistically significant in all three technologies we can extrapolate the sample data to the population data with confidence. Further analyzing the data from the SUS questionnaire, the data shows that CAVE proved to be 47% better than the PC and just 14% worse than the VIVE Head-Mounted display in terms of inducing presence as transportation.

Looking at the Presence Questionnaire domains, the data is consistent with previous studies relating visual fidelity as means of inducing presence as shown by the difference of averages in the Visual Aspect domain between CAVE and PC. The higher graphical capabilities and display of imagery of the CAVE when compared to said capabilities of the PC is portrayed as expected in terms of presence with the CAVE being more presence inducing in this domain than the PC. However we expected the difference between CAVE and HMD to be rather small in this domain but the data shows otherwise. In fact, looking at the significance obtained in the Wilcoxon and averages of all three technologies, we notice that the gap between the CAVE and HMD is higher than the gap between CAVE and PC, contradicting our expectations.

Regarding the Interaction domain, the data is more consistent with our expectations. The Wilcoxon test applied to the pair CAVE-VIVE showed that there is no statistically significant difference between CAVE and VIVE in this domain. The VIVE average in this domain being higher than the CAVE occurred by chance and there are no differences between the two. One possible explanation is the fact that we opted to not use the VIVE hand-tracked controllers as means of uniformization and isolation of study variables. If the interaction involved was, for example pushing objects, the data could have shown otherwise since the VIVE controllers would come into the equation. When looking at the averages of both CAVE and VIVE when compared to the PC we notice quite a large gap. This was quite expected since CAVE and VIVE use a more natural way of interaction and this natural way of interaction is provided by the correctly mapping of human body movement to the system reactions which is reported to induce higher levels of presence[43]

Regarding if the system portrayed dynamics (visually and behaviorally) that are consistent with their real world counterparts, or in other words, the

consistency with the real world, we find that Wilcoxon showed no statistically significant differences between CAVE and PC. On the other hand, the Wilcoxon showed differences between the CAVE and the VIVE, with this last one scoring higher than both CAVE and PC.

This domain included a question regarding how responsive was the environment to actions that the user initiated and here we may find a part of the explanation to why the VIVE scored higher than both CAVE and PC since VIVE had very little delay when compared to the CAVE. Since the CAVE system displays at a much higher resolution than the VIVE, naturally the frames per second in the CAVE system were lower than the VIVE system resulting in a more stuttering experience inside the CAVE when compared to the VIVE.

But since the display of the PC is similar to the VIVE that does not explain why the PC scored lower than the VIVE by this fact alone. In fact, for this question, the CAVE scored the lowest with the PC scoring higher than the CAVE and VIVE scoring higher than both CAVE and PC, yet let's keep in mind that there are no differences in this domain between CAVE and PC so let's analyze other question in this domain.

The other two questions in this domain portray the subjective feeling by the user that the system correctly mimicked the real world and these questions are what dragged the score of the PC down. In both the PC scored the lowest. This was quite surprising since the PC system is more mature system than the other two technologies. For example, to "look" around the environment every single user knew that by moving the mouse around, the camera would turn and could anticipate very well the actions of the system. Yet, in the question "Were you able to anticipate what would happen next in response to the actions that you performed?" the PC scored the same as the CAVE system which is comparatively newer.

Concerning the workload of all three systems in the task of finding apples in our study, the data obtained through the Raw NASA TLX shows that there are no statistically significant differences in all domains of this test except for the Physical Demand domain between the pair PC-CAVE. This was to be expected since the task performed in PC involved only upperlimb movement in a seated position while the task performed in the CAVE and VIVE involved moving your head, arms and walking around. In addition to this, the PC scored the best in this domain which corroborates the aforementioned sentence. We expected that the task would be easier to perform on a CAVE in comparison to the PC but the domain Effort showed no differences in all

three technologies. However, this does not necessarily negate that, since all participants were most comfortable with the PC system than the CAVE system which they never experienced before. This mismatch in technology comfort could have limited the CAVE in this domain. On the other hand all three technologies scored very good in the Effort domain, perhaps showing that the task was fairly simple and didn't push the bounds of each system. Further studies should elongate on this with more difficult tasks.

Also, regarding the Frustration domain, all three systems showed no statistically significant differences but the score obtained mapped to very low levels of frustration when doing the apple searching task but. Again, the fact that all users had prior experience with interacting with a PC may have had a weight in this scoring system. Our assumption was that performing a task in a natural interaction system like the CAVE and VIVE should lead to lower levels of frustration than performing the same task in a less natural interaction system but again, the data shows no differences in all three systems.

Chapter 6

Conclusions

In recent years Virtual Reality has become the interest of many researchers and companies alike, culminating in rapid development of VR. This thesis fits in the attempt to further one of the means of providing Virtual Reality - the CAVE. This thesis also arose from the wish of developing a CAVE system in M-ITI which should be multi-purpose while fairly low-cost.

Then, investigation of what was already done in terms of low-cost CAVEs was made culminating in three targets - GIVA CAVE, TIVS CAVE and CryVE. These three CAVEs were chosen as means of comparison because all three were deployed in a similar room space to what was required for our CAVE. Furthermore, all three CAVEs implement their solutions with low-cost in mind while keeping the performance as close to professional solutions - something we established early on as a requirement for our CAVE.

In our investigation we found that two of the CAVE components that weighed heavily in the cost of developing a CAVE was the tracking system with thousands of dollars spent and the CAVE software to operate applications inside of the CAVE with the plus of the CAVE calibration being a cumbersome and complex process in most cases.

To counter this, we decided to include a single Microsoft Kinect as our CAVE's tracking equipment because of their low cost (aprox. 200 €) and develop our own custom calibration software to provide a complex-free experience of calibration and make this software available to potential CAVE developers. This also has the plus side of potentially generating more interest in CAVE systems as their setup complexity is lower.

The completion of the KAVE with the goals of driving the price of CAVE system down was a success with the KAVE being much lower cost than the

three other CAVEs described previously while retaining much higher graphical fidelity. The calibration software was also successfully developed and contributed to the complex-free setup of the KAVE, as proposed early on.

With the KAVE successfully implemented, we evaluated it in terms of presence - using tools found in the literature, namely the SUS questionnaire and the Presence Questionnaire - and in terms of workload of the system using the NASA Task Load Index (NASA TLX). We also added evaluation of a PC system and Head-Mounted display to compare the data obtained from the evaluation of the KAVE. The data obtained from this study added to existing presence studies made previously.

When looking at the results, the data showed that Head-Mounted Display (VIVE) induced higher degrees of presence than our CAVE, contrasting the reports found in the literature stating the contrary - that CAVEs induce higher degrees of presence than the HMDs. These reports are a bit dated and facing the recent advances of HMDs we assumed that our CAVE would score lower than the HMD, which proved correct.

We also verified that natural interactions such as the CAVE and HMD are more presence inducing than less natural interaction system such as the PC. This data proved consistent to previous reports found in the literature.

The system workload results showed that, apart from the physical demand of a task, all other domains of the NASA TLX showed no differences between all three systems, leading to believe that performing a task in a PC, CAVE or HMD leads to the same levels of demand (again, apart from physical demand).

In terms of future work, ideally it would be interesting to have had the opportunity to compare all the low-costs CAVEs described previously in terms of presence to add value to the comparison of those CAVEs and our solution done in this paper. This proved unfeasible since it would require running the same procedure (also the same virtual environments) on each CAVE to be able to compare the data. There is a lack of a standardized way of assessing presence in CAVEs. While the questionnaires are somewhat useful, since CAVEs are not easily accessible, applying the same procedure across different CAVEs is very difficult.

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APPENDIX

APPENDIX A

Slater Usoh Steed Questionnaire (SUS)

1. Please rate your *sense of being* in the virtual environment, on a scale of 1 to 7, where 7 represents your *normal experience of being in a place*.
2. To what extent were there times during the experience when the virtual environment was the reality for you?
3. When you think back to the experience, do you think of the virtual environment more as *images that you saw* or more as *somewhere that you visited*?
4. During the time of the experience, which was the strongest on the whole, your sense of being in the virtual environment or of being elsewhere?
5. During the time of your experience, did you often think to yourself that you were actually in the virtual environment?

APPENDIX B

Presence Questionnaire

This questionnaire uses a 1-7 point scale. Please write a number from 1 to 7 in front of each question that most closely matches your experience.

Visual Aspects

1. How much did the visual aspects of the environment involve you?
2. How aware were you of your display devices?
3. How completely were you able to actively survey or search the environment using vision?
4. How closely were you able to examine objects?
5. How well could you examine objects from multiple viewpoints?
6. How much delay did you experience between your actions and expected outcomes?
7. How much did the visual display quality interfere or distract you from performing assigned tasks or required activities?

Interaction

8. How natural did your interactions with the environment seem?
9. How natural was the mechanism which controlled movement through the environment?
10. How aware were you of your control devices?
11. How compelling was your sense of moving around inside the virtual environment?
12. How distracting was the control mechanism?
13. How much did the control devices interfere with the performance of assigned tasks or with other activities?

Consistency with the real world

14. How responsive was the environment to actions that you initiated (or performed)?
15. How much did your experiences in the virtual environment seem consistent with your real-world experiences?
16. Were you able to anticipate what would happen next in response to the actions that you performed?

Subjective factors

17. How much were you able to control events?
18. How involved were you in the virtual environment experience?
19. How quickly did you adjust to the virtual environment experience?
20. How proficient in moving and interacting with the virtual environment did you feel at the end of the experience?
21. Did you learn new techniques that enabled you to improve your performance?

APPENDIX C

