Immersive technologies for virtual reality - Case study : flight simulator for pilot training

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Année académique : 2018-2019
URI/URL : http://hdl.handle.net/2268.2/6443

IMMERSIVE TECHNOLOGIES FOR VIRTUAL REALITY

CASE STUDY : FLIGHT SIMULATOR FOR PILOT TRAINING

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With a view to obtaining the diploma of Master's degree in Business Engineering specialising in Supply Chain Management and Business Analytics, Digital Business
Academic year 2018/2019

Acknowledgements

First of all, I would like to thank my supervisor, Prof. Michaël Schyns, for his great guidance throughout the different steps of the development of this thesis and for providing me with a room for the experiments. Moreover, I am grateful to Florian Peters for his advice, especially concerning the analysis of the results of the study.

I am also thankful to ASL Airlines Belgium for putting their trust in me for the development of the proof of concept of the flight simulator. More specifically, I would like to thank Jean-Marc Urbani and Rinesh Ramkissoon for giving me the opportunity to discover the world of aviation and air freight, as well as for providing me with all the information I needed during this internship. Many thanks to Mathieu Dengis for his technical insights and for the time he spent on evaluating the flight simulator.

I am grateful to my colleagues who supported me during the writing of this master thesis. Especially, I would like to thank Alexis Jacquemin, Aubert Bourguignon and Kevin Verbruggen, who were part of the team working on the proof of concept for ASLB.

Special thanks to Jessica Simon, postdoctoral researcher in psychology, for guiding me through the methodology of my study on immersion, for providing me with the required materials and for helping me to define the relevant analyses to be carried out in my comparative study.

Finally, I am very thankful to my family, especially my mum, my dad and my sister for their help and continuous support during the past few months. I would also like to thank my boyfriend, who has always been supportive and who was able to cheer me up when I needed it.

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List of Abbreviations

AR	Augmented Reality
ASLB	ASL Airlines Belgium
CAVE	Cave Automatic Virtual Environment
FBS	Fixed-Base Simulator
FFS	Full Flight Simulator
G	Hi5 VR Glove
LM	Leap Motion
MR	Mixed Reality
PoC	Proof of Concept
VR	Virtual Reality
WSD	Within-subject design

Chapter 1: Introduction

Virtual reality (VR) has become a buzzword over the past few years. However, virtual reality was already very popular in the 1980s. Research into the technology was in full swing. In the 1990s, many consumer headsets were released, and many entertainment companies developed VR products such as arcade machines. Nevertheless, the technological capabilities could not match the public's expectations at the time and public interest in VR has gradually declined (Sherman, 2018; Steinicke, 2016). In 2013, VR came back in the spotlight thanks to technological advances.

More than just a buzzword, virtual reality has the potential to disrupt the way companies operate. Already in the 1990s, several companies reported increased productivity and reduced costs after adopting VR for their operations (Brooks, 1999). These days, it is considered as a key technology to invest in for businesses (Gartner, 2018). From design review to training by the way marketing, various applications are deployed across many industries. Moreover, research in the field increased in recent years.

This master thesis seeks to analyse two different aspects of immersive virtual reality, each one defining a distinct research question. First, a management approach of the technology is applied to assess whether VR can respond to the needs of a company. To that end, a case study on ASL Airlines Belgium, a Belgian cargo airline, is conducted. Therefore, the first research question to be addressed is the following:

Is immersive virtual reality a potential tool for pilot training in the aviation industry?

The purpose is to evaluate the technical feasibility of a VR system for pilot training. Current training methods are either not realistic or expensive. An immersive VR flight simulator would be a cheaper and more immersive solution. Nevertheless, the potential of such a solution must be assessed before taking the decision to modify the entire training system. For that purpose, the first step is to carry out a market research of existing solutions. Furthermore, it is important to determine if a new product could differentiate itself from the competition. Although VR proves to be a powerful tool for training (Martirosov & Kopecek, 2017), its validity from an educational point of view in the context of pilot training must be checked. However, this goes beyond the scope of this thesis.

In addition to this managerial perspective, a more technical approach of the technology is also covered. The main technological component of an immersive VR system is the headset, which occludes the real world and immerses the user in a virtual world. On top of that, many immersive technologies are developed in order to increase the levels of immersion and presence in the virtual environment. The focus of this work is mainly on hand tracking technologies, although there exist immersive systems enhancing other components of a VR experience. These technologies are the topic of the second research question of this thesis, which can be formulated as follows:

Which immersive technology is the most suitable for hand tracking in virtual reality?

To answer this question, different features must be taken into account, such as the induced level of presence, technological capabilities and the goal of the VR application. The two hand tracking systems compared in this dissertation are the Leap Motion controller and VR data gloves. To determine which VR gloves to use, different gloves are analysed. The comparative study is then carried out.

As a student in Digital Business, a master's degree which combines management and computer science, this thesis has an additional objective: developing a proof of concept of a virtual cockpit for pilot training in VR. Therefore, in addition to evaluating the theoretical feasibility of this solution for ASLB, I programmed a proof of concept with the game engine Unity3D. Moreover, immersive technologies were implemented and tested in this virtual environment. Thus, it is also used for the comparative study.

The remainder of thesis is structured in the following way. To begin with, the history of virtual reality is briefly presented, and the term *virtual reality* as well as its key components are defined. Then, a literature review on both business applications of VR and the notions of immersion and presence is provided, in order to cover the two research questions. The subsequent chapter is dedicated to the case study on ASL Airlines Belgium. It includes a presentation of the case and a competitive analysis of flight simulators leading to a concise description of a differentiation strategy. Furthermore, the developed proof of concept is presented, and different immersive technologies are analysed. The Leap Motion and the VR gloves are then empirically compared in a comparative study on immersion. Next, more information about my role of project manager in the development of the virtual cockpit is provided in the Project Management chapter. Finally, the last chapter summarizes the key findings of the thesis.

Chapter 2: Virtual reality technology

Virtual reality and immersive technologies in general have attracted a lot of attention in recent years. However, virtual reality is not a new concept, although the technology has well progressed since its early days. In the first section of this chapter, the historical background of virtual reality is presented, tracing some important milestones. Then, it is important to clarify what virtual reality really is, given that it is the central concept of this thesis. For this reason, the second section is dedicated to defining virtual reality as well as its key elements, and to presenting the different virtual reality systems available.

2.1 HISTORICAL BACKGROUND

Although the term *virtual reality* was not yet associated to the research area, the first developments in that field can be traced back to the 1960s.

One of the first famous pioneers was Morton Heilig, a cinematographer who wanted to enhance the audience experience by involving all human senses. In 1962, he built and patented the first true multisensory VR system, called *Sensorama* and depicted in Figure 2.1, which he already imagined in the 1950s (Steinicke, 2016). It featured a 3D display and its user could for example experience a motorcycle ride through Manhattan, not only including sights and sound, but also smell, vibration and wind (Sherman, 2018).

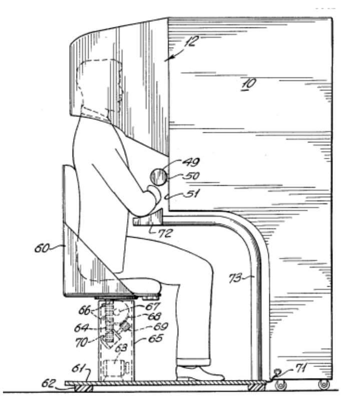


Figure 2.1: Sketch of the *Sensorama* (reprinted from https://en.wikipedia.org/wiki/Sensorama)

Another important milestone was the development in 1961 by Charles Comeau and James Bryan of *Headsight*, the first head-mounted display fabricated including a motion-tracking system determining the direction of the head (Steinicke, 2016). However, head movements were linked to a camera that would move accordingly in order to display a video from a real remote location and thus, the HMD was not linked to any virtual environment (Mihelj, Novak, & Beguš, 2014).

In 1965, Ivan Sutherland, who is considered as "*one of the godfathers of computer graphics*" (Steinicke, 2016, p.19), wrote his famous essay *The Ultimate Display* in which he describes a futuristic display that would immerse the user into a world generated by a digital computer and impossible to differentiate from the real world (Steinicke, 2016). Brooks (1999) paraphrased the visionary view of Sutherland in the following way:

> *Don't think of that thing as a screen, think of it as a window, a window through which one looks into a virtual world. The challenge to computer graphics is to make that virtual world look real, sound real, move and respond to interaction in real time, and even feel real*. (p.16)

Only 3 years after publishing his paper, Sutherland created the first HMD connected to a virtual environment (Mihelj et al., 2014), considered in the field of VR as the first real HMD system (Steinicke, 2016). Called the *Sword of Damocles*, the helmet displayed a perspective image thanks to two small screens showing two-dimensional images in front of the user eyes, creating the illusion of seeing an object in 3D. Using head position sensors, the display adjusted the image shown to the user as he/she moved (Sutherland, 1968). Nevertheless, as shown in Figure 2.2, the motion tracking system was attached to the ceiling and therefore the display was quite cumbersome.

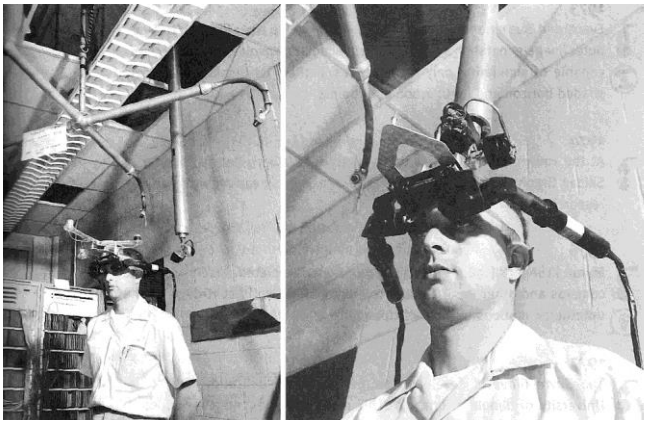


Figure 2.2: *Sword of Damocles* (reprinted from https://www.ulyces.co/news/le-premier-casque-de-realite-virtuelle-a-ete-invente-en-1968/)

Even though great developments had been made, an important component of virtual reality was still missing at that point: interaction. Myran Krueger, a computer artist, filled this gap in 1969 by developing the first virtual environments reacting to gestures and movements of the user (Steinicke, 2016). The system used video cameras as well as pressure sensors in the floor in order to define how to move virtual objects (Mihelj et al., 2014).

Around 1985, the VR pioneer Jaron Lanier created and popularized the term *virtual reality* (Mihelj et al., 2014). He was also the founder of the Visual Programming Lab (VPL), which developed and commercialized different virtual reality products at the end of the 1980s such as the first motion recognition glove for sale, the VPL Dataglove, and the first commercial virtual reality HMD, the EyePhone (Steinicke, 2016; Mihelj et al., 2014).

Another historical milestone worth mentioning is the creation of the CAVE (Cave Automatic Virtual Environment), a cubic room made of screens (Cruz-Neira, Sandin, DeFanti, Kenyon, & Hart et al., 1992) commonly used nowadays for VR applications.

Throughout the 1990s, a lot of progress was made in the field and the technology was adopted by several companies in order to cut down costs, achieve a better productivity and enhance team communication (Brooks, 1999). Moreover, the gaming and entertainment industries particularly invested in immersive experiences because there was a substantial enthusiasm for VR among the population. Nevertheless, the interest of the public rapidly declined because the technology did not match their enormous expectations and the hardware was too expensive (Sherman, 2018; Steinicke, 2016).

To analyse the following years of the development of VR, the well-known Gartner Hype Cycle for emerging technologies is used. It depicts the common evolution pattern of new technologies, from early interest and enthusiasm through disillusionment to eventual mainstream adoption (Fenn, Raskino, & Burton, 2017). In Figure 2.3, the different appearances of VR in the Gartner Hype Cycle for emerging technologies are summarized. As it can be seen, in 1995, the first Hype Cycle ever published already included VR and positioned it in the Trough of Disillusionment stage. Indeed, the expectations towards the technology exceeded its capabilities. This is probably why afterwards, VR disappeared from the Hype Cycle for several years. However, VR is back in 2013, even though still in the Trough of Disillusionment. This comeback was fostered by the launch of the Oculus Rift DK1, an HMD for video games developers produced by Oculus VR thanks to a Kickstarter campaign which raised more than 2 million dollars (Kickstarter, n.d.) This HMD outperformed all existing HMDs in terms of field of view, resolution, weight, and especially, costs. Moreover, it featured orientation tracking (Steinicke, 2016). Within the next 3 years, other significant advances in the field occurred, such as the acquisition of Oculus VR by Facebook, the launch of the Google Cardboard and the release of the HTC Vive. All this progress brought VR into mainstream and helped the technology to reach the Slope of Enlightenment in 2016. At this stage, the true value of the technology is clearer, and an increasing number of companies experiment potential applications. Between 2016 and 2017, VR slightly moved towards the Plateau of Productivity and would reach it within 5 years. The market penetration among the target audience lies between 5 and 20% (Fenn et al., 2017). Gartner (2018) predicts that 70% of companies will be testing immersive technologies (encompassing VR, augmented reality and mixed reality) by 2022, while 25% will already use it in production. It is also interesting to note that VR disappeared from the Hype Cycle in 2018 because Gartner considers the technology as almost mature and thus, it cannot be included in an analysis of new technologies.

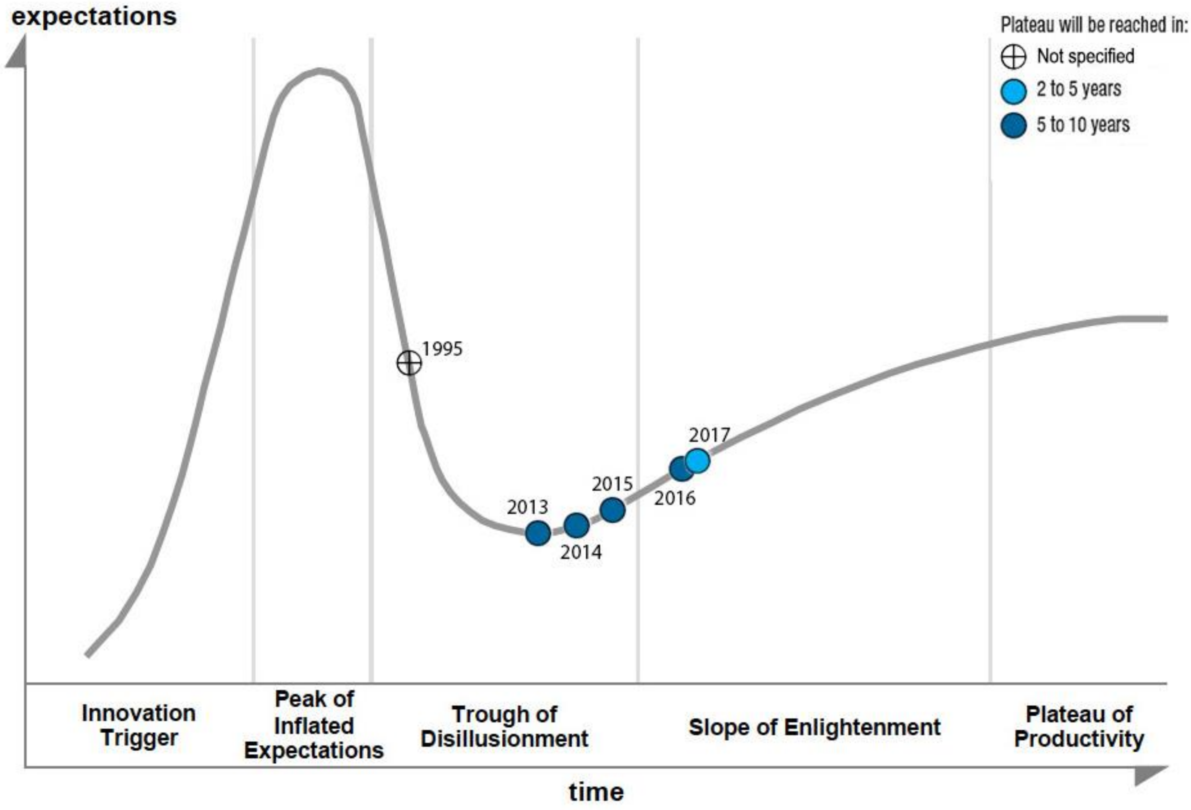


Figure 2.3: Gartner Hype Cycle of Virtual Reality

2.2 HOW CAN VIRTUAL REALITY BE DEFINED?

Nowadays, it is frequent to hear about Virtual Reality, Augmented Reality (AR) as well as Mixed Reality (MR). However, because these notions and their specific features get sometimes mixed up, a first step in defining and understanding VR is to clearly distinguish it from AR and MR. To this end, a useful tool is the *Reality-Virtuality (RV) Continuum*, a concept introduced by Paul Milgram. This continuum can be seen as a continuous scale determining the extent to which the environment is modelled by a computer, as illustrated in Figure 2.4. The left pole encompasses Real Environments (RE), which are completely unmodeled, while the right pole encompasses Virtual Environments (VE), which are completely modelled and only composed of virtual objects. AR and MR are located in the middle of the continuum because their environments are partially modelled (Milgram & Kishino, 1994); AR environments consist of real scenes that are enhanced with computer graphics (Milgram et al., 1995) and are thus close to RE, whereas MR is a broader concept that includes any partially-modelled environment (Milgram & Kishino, 1994). On the other hand, VR technologies specifically use completely synthetic worlds (VEs). For this reason, the environment might be realistic but real-world physical laws do not have to hold, as opposed to AR environments which are constrained by the laws of physics (Milgram et al., 1995).

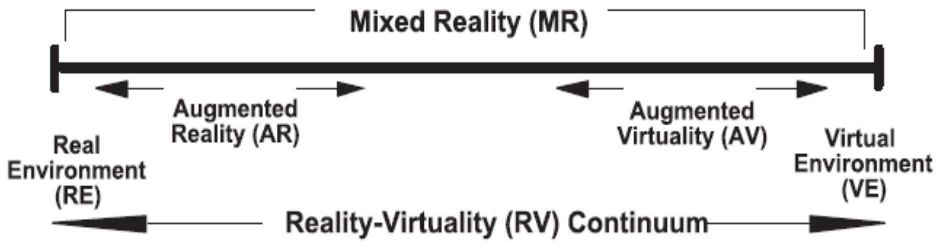


Figure 2.4: *Reality-Virtuality Continuum* (reprinted from Milgram & Colquhoun, 1999, p. 9)

This element is indeed present in the definition of VR given by the Oxford Dictionary: "*The computer-generated simulation of a three-dimensional image or environment that can be interacted with in a seemingly real or physical way by a person using special electronic equipment, such as a helmet with a screen inside or gloves fitted with sensor*" ("Virtual Reality," n.d.). As for the consulting company Deloitte, it describes VR as a technology that "*creates a fully rendered digital environment that replaces the user's real-world environment" and "features body- and motion-tracking capabilities*" (Deloitte, 2018c, p. 76).

Despite all the interest of the scientific community in VR, there does not exist one common definition in research. Most researchers give and use their own definition of VR, which mostly depends on their background and area of study (Muhanna, 2015).

After the term *virtual reality* was coined by Jaron Lanier, the global interest in the field increased and, in the beginning of the 1990s, many researchers attempted to define the expression. Yet, most of these definitions focused on the technological component of VR. For instance, Coates (as cited in Steuer, 1992), defines VR as "*electronic simulations of environments experienced via head-mounted eye goggles and wired clothing enabling the end user to interact in realistic three-dimensional situations*" (p. 74). Steuer (1992) criticized those hardware-focused definitions and wanted to create a definition based on "*a particular type of experience*" (p. 74). To that purpose, the concepts of presence and more specifically telepresence are essential. Presence refers to "*the sense of being in an environment*" (p. 75) and is a natural perception occurring without any medium, whereas telepresence refers to "*an experience of presence in an environment by means of a communication medium*" (p. 76). The degree of telepresence of an experience hinges upon how much the feeling of presence related to the mediated environment prevails over the one related to the direct physical environment, even if both are perceived simultaneously. Using this concept, Steuer (1992) describes VR as an *"environment in which a perceiver experiences telepresence*" (pp. 76-77).

In the following years, most definitions in the literature followed suit and dropped the hardware-based perspective. For example, the Professor of Computer Science Brooks (1999) defined a VR experience as "*any in which the user is effectively immersed in a responsive virtual world. This implies user dynamic control of viewpoint*" (p. 16). More recently, Dioniso, Burns III, & Gilbert (2013) gave the following definition: "*computer-generated simulations of three-dimensional objects or environments with seemingly real, direct, or physical user interaction*" (p. 1). Because all definitions are different, it is probably more interesting to describe VR by using the components shared by these definitions. These key elements essential to any virtual reality experience were identified by Sherman (2018) and will be analysed in the next subsection.

2.2.1 Key elements of a virtual reality experience

The first element is the **virtual world**. It consists of a description of objects in a space as well as the rules dictating the behaviour and the relationships of those objects (Sherman, 2018). As already stated at the beginning of this section, VR is characterized by fully-modelled environments (Milgram & Kishino, 1994), a rule the virtual world consequently must follow.

Then comes **immersion**. Immersion and presence (or telepresence) are two recurrent concepts in the VR literature but their meaning can vary from one scientific paper to another. For this reason, Slater & Wilbur (1997) defined these terms and explained why they differ from one another, while being probably strongly correlated. Immersion is objective and directly linked to the technology. It illustrates the fact that the physical body of the user enters the medium (Sherman, 2018), which is the virtual world in this case. The level of immersion of a system depends on the extent to which it is faithful to reality in terms of sensory modalities. Presence on the other hand is a subjective "*human reaction to immersion*" (Slater, 2003, p. 1), a "*state of consciousness*" (Slater & Wilbur, 1997, p. 603). Slater's concept of presence corresponds to the one of Steuer (1992) given hereinabove: the more the virtual environment predominates over the surrounding physical environment, the more the user is present. These concepts will be analysed more deeply in section 3.3 but overall, immersion relates to physical immersion, whereas presence refers to mental immersion. Physical immersion is a key characteristic of VR and is obtained by including synthetic stimuli (which can be visual, audio and haptic) in the virtual environment as a result of the user's actions (Mihelj et al., 2014).

Directly influencing the immersion level, **sensory feedback** is another key element of VR. The physical position of the user influences the sensory feedback given by the system, which is most of the time visual but could be of any kind. For instance, the displayed image should change according to the position and orientation of the user's head. To this end, position tracking of different parts of the body is crucial.

The fourth key component of any VR experience is **interactivity**. Of course, in order to create a lifelike experience, the user has to be able to interact with the virtual environment and its objects. It means that the user's actions should affect the virtual world (Sherman, 2018). There exist different ways to interact with virtual environments: travel, selection and manipulation (Bowman & Hodges, 1999). Travel refers to the change of one's view point from one virtual location to another. Selection and manipulation respectively correspond to choosing a virtual object and changing its properties, such as position, orientation, shape and so on.

A new definition of VR including all these components can be given: "*Virtual reality is composed of an interactive computer simulation, which senses the user's state and operation and replaces or augments sensory feedback information to one or more senses in a way that the user gets a sense of being immersed in the simulation (virtual environment)*" (Mihelj et al., 2014, p.1). Even if this definition encompasses all VR systems, different types of VR systems exist.

2.2.2 Categorization of VR systems

A criterion that can be used to classify VR systems is the display technology. Three different categories can be identified: hand-based systems, stationary systems and head-based systems (Sherman, 2018).

Hand-based systems provide visual information through smartphones, tablets or any device small enough to be held in the user's hands. Interaction with this type of system is most of the time achieved thanks to an interface visible on the screen. However, hand-based systems show more potential in the augmented reality field (Sherman, 2018) and are not usually used for VR experiences.

When the user does not have to wear or carry any hardware, one talks about **stationary displays**. They can be of different types. The first one is called *monitor-based VR*, consisting of 3D graphics displayed on the monitor of a desktop system (Muhanna, 2015), also called fishtank VR (Sherman, 2018). It can be considered as VR because of the head tracking impacting the displayed images, along with the interaction enabled either by regular means, e.g. mice and keyboards, or by 3D-specific interaction devices, e.g. wired gloves (Costello, 1997). Another type of stationary VR system involves a single projector and a large screen (Muhanna, 2015). In some cases, it requires special goggles to create 3D scenes, e.g. the ImmersaDesk system shown in Figure 2.5.

Figure 2.5: The ImmersaDesk, a stationary VR system (reprinted from https://www.polymtl.ca/rv/Activites/20--_Cave/EnvRV/)

Finally, the last stationary device type is the *surround VR display*. As the name suggests, the participant is surrounded by several screens (Sherman, 2018). The most common example of such a technology is probably the Cave Automated Virtual Environment (CAVE), shown in Figure 2.6. It is a cubic room whose walls and sometimes floor and ceiling are made of screens using either projected images (Cruz-Neira et al., 1992), or, more recently, flat panel monitors. To create a stereoscopic view, the image is displayed twice with some overlapping and the user has to wear shutter glasses (Sherman, 2018). For interaction, an input device with several buttons, called a wand, is utilized (Cruz-Neira et al., 1992).

Figure 2.6: CAVE, a surround VR display (reprinted from http://www.visbox.com/products/cave/viscube-m4/)

Head-based systems are probably the VR systems that come in most people's mind when they hear or talk about VR. Some of them are called *occlusive head-based displays*, also known as head-mounted displays (HMDs), a first category that truly isolate the user from the real world, as shown in Figure 2.7. The person gets a visual image no matter the direction he/she looks in, creating a 360° field of regard. The helmet is composed of two small screens displaying computer-generated images in 3D, and a position-tracking system, making the experience natural and realistic. Different input devices such as game controllers, gloves or even hand tracking devices can be used for interaction purposes. However, cables connected to the headset might impede the experience by creating physical constraints (Sherman, 2018).

Figure 2.7: The HTC Vive, an HMD (reprinted from https://aitec-informatique.fr/baisse-de-prix-annonce-pour-le-htc-vive-et-nouveau-casque-vr/)

The other category of head-based systems is *smartphone head-based displays*, depicted in Figure 2.8. The boom of smartphones has been a huge opportunity for the VR industry: they are able to display 3D computer graphics and have a built-in position tracking system. Those displays require a phone holder with special lenses to make the experience more comfortable, given that the screen is very close to the eyes. Supplementary input devices can be included. The most popular system of this type is probably the Google Cardboard, released by Google in 2014. Other systems are more sophisticated, e.g. Samsung Gear VR which does not have to be held in front of the eyes and features additional electronics (Sherman, 2018).

Figure 2.8: Google Cardboard on the left, Samsung Gear VR Innovator Edition on the right (reprinted from https://www.oneclickroot.com/android-apps/google-cardboard-apps-now-compatible-with-your-gear-vr/)

VR systems can also be classified according to the level of immersion they provide, as presented in Table 2.1. Even if a minimum level of immersion is a defining characteristic of VR, some systems are more immersive than others. Hand-based and monitor-based systems are considered non-immersive because the user is barely isolated from the real world and interaction is quite limited. Systems using a large screen and a projector are semi-immersive (Costello, 1997; Muhanna, 2015). As for surround VR systems such as CAVEs, they are sometimes seen as semi-immersive (Costello, 1997), but most of the time as fully immersive (Miller & Bugnariu, 2016; Muhanna, 2015; Mujber, Szecsi, & Hashmi, 2004). Head-based systems are fully immersive because the user hardly perceives the real world and gets a 360° field of view (Costello, 1997; Muhanna, 2015). Nevertheless, it should be noted that the level of immersion does not only depend on the display but is rather the result of a complex interaction of many factors (Costello, 1997).

Non-immersive	**Semi-immersive**	**Fully immersive**
• Hand-based systems • Monitor-based systems	• Large screen projector systems (e.g. ImmersaDesk)	• HMDs • CAVEs

Table 2.1: Classification of VR systems according to the immersion level

Chapter 3: Literature Review

The goal of this literature review is twofold. First, as part of a master thesis in management, the purpose of analysing a disruptive technology is to identify the potential benefits of its implementation in business operations. It is important to determine in which context it is relevant for a company to invest in the technology, i.e. to determine use cases. For this reason, section 3.2 is dedicated to business applications of VR. Second, because this thesis aims to analyse immersive technologies, immersion and some related concepts must be introduced. To that end, various theoretical positions are presented in section 3.3, along with previous studies about immersive technologies. But to start with, the first section briefly presents the methodology used to carry out the literature review.

3.1 METHODOLOGY

To gather relevant information about business applications, I first looked for virtual reality applications in the Scopus database, in Google Scholar and in reports from the main consultancy companies, without restricting the search to specific industries. Then, I searched for the main applications in every major industry, except for entertainment and education. I excluded entertainment because in that context, a VR experience is a new type of product rather than a mean to create real added value for the company operations. As for education, a lot of research is conducted on the use of VR. However, I do not consider schools and universities relevant for a section about business applications. It should be noted that this does not exclude training in a corporate context. For this reason, the term *training* was preferred to the term *education* for the research. A lot of articles were skimmed, and the literature worthy of further analysis was preselected based on the title and abstract. I also tried to illustrate the possible applications discussed in research papers by finding concrete examples of companies using the technology. These examples can come from research papers but also from a simple Google search. Each subsection within section 3.2 explains the main applications of VR in one specific major sector, apart from the last subsection which summarises the presented applications using the main business functions as classification criteria.

With regard to immersion and presence, I mainly used the Scopus database. First, I searched for "virtual reality immersion presence", analysed a few articles and, using backward search, identified the main authors who worked on those concepts and their definition. Then, I examined more deeply the research of those authors. Finally, studies about immersion and presence were skimmed.

3.2 BUSINESS APPLICATIONS OF VIRTUAL REALITY

Although some VR applications were already in test phase some years before, it is only at the end of the 1990s that a few companies started using them on a regular basis in their operations for cost, communication and productivity purposes (Brooks, 1999). Nowadays, even if most people associate VR with the gaming industry, the technology has shown a very wide range of applications for businesses and many companies resort to it. This surge in adoption has been encouraged in the last five years by the recent improvements of VR capabilities as well as the decreasing prices of hardware (Deloitte, 2018d). In this section, potential business applications from research papers together with actually-implemented applications in different fields are analysed.

3.2.1 Retail

In the retail industry, VR is particularly relevant for **marketing** purposes. By providing richer and more engaging consumer experiences, it is possible to increase brand awareness, reinforce brand values and boost customer loyalty (Barnes, 2016). Indeed, it has been proven that using a virtual store can induce higher purchase intentions and brand recall than a traditional physical store through the emotions and sense of presence it creates (Martínez-Navarro, Bigné, Guixeres, Alcañiz, & Torrecilla 2018). In the context of e-commerce, it could be a solution to the lack of interaction with the products, which is often seen as the biggest disadvantage of e-commerce over physical stores (Bonetti, Warnaby, & Quinn, 2018). Moreover, VR can be used in physical stores in order to enhance the shopping experience. For example, some apparel retailers created virtual catwalk experiences (Barnes, 2016), such as Tommy Hilfiger which introduced VR headsets in their biggest stores in 2015, enabling customers to attend the fashion show of the brand in the front row (Tabuchi, 2015). VR also has a particular potential in the purchasing process for customised products (Barnes, 2016; Bonetti et al., 2018) because customers can actually visualize the final result before purchasing the product. It has been implemented by Ikea and Lowe's which enable people to personalize and experience their own kitchen in VR (Ikea, 2016; Barnes, 2016), and by Audi which offers customers an experience of their configured car (Audi, 2017). All these companies use VR headsets to provide an immersive customisation process. Besides, in the real estate sector, VR can have a positive impact on marketing activities. When presenting a house to prospective buyers through visual marketing, a VR tour with a VR headset turns out to be more effective than pictures in making them want to visit the house in real life. Furthermore, it is a great solution for remote or foreign potential buyers (Brenner, 2017). For on-sale unbuilt properties, VR visualization can "*bridge the cognitive gap between pre-sale products and actual products*" (Juan, Chen, & Chi, 2018, p.12). Therefore, it positively influences purchase intentions. In some cases, the house is fully interactive, and the user can directly modify some of its characteristics such as the wallpaper and floor covering (Ozacar, Ortakci, Kahraman, Durgut, & Karas 2017). Several companies, such as Matterport and Bricks & Goggles, can create 3D models usable for VR, using either pictures of real-world properties or construction designs (KPMG, 2018).

Market research can also benefit from the technology. VR is useful when designing new stores because it can decrease development costs and be more effective (Bonetti et al., 2018). It is also an interesting low-cost way to analyse consumer decision-making (Barnes, 2016). On the one hand, data on consumer behaviour, such as eye tracking, can be easily collected and on the other hand, it provides a realistic controlled shopping experience and thus, increases the validity of findings in comparison to other lab-based desktop methods (Meißner, Pfeiffer, Pfeiffer, & Oppewal, 2019). Nestle, Unilever and Cadbury are companies that successfully implemented VR in their market research activities (Rutgers Online, 2014).

3.2.2 Healthcare

The healthcare industry is of particular interest in research as well. The field of **surgical training** has been extensively investigated and a large number of studies highlighted the positive results of VR training in general (Slater & Sanchez-Vives, 2016). Traditionally, the training procedure consists in observing the senior surgeons and performing surgeries with graduated responsibility over a long period (Gallagher et al., 2005; Lewis, Aggarwal, Rajaretnam, Grantcharov, & Darzi, 2011). VR surgical training is a great alternative for several reasons. First, it has been proven that using VR training significantly improved the surgeons' performance in the operating room, resulting in a faster and less error-prone performance (Seymour et al., 2002). This increased performance can be due to the confidence gained during VR rehearsals (Locketz et al., 2017). Second, VR gives trainees the opportunity to train in a risk-free and controlled environment (Gallagher et al., 2005), without putting the life of a patient at risk. Moreover, VR simulators can create various contexts such as emergency situations for the same surgical procedure (Slater & Sanchez-Vives, 2016) but also allow for standardised tasks, which facilitates the performance measurement through diverse metrics (Lewis et al., 2011). For example, the University School of Medicine in Atlanta uses VR surgical training, which decreases the number of mistakes in comparison to conventional training (Accenture, 2018). Apart from creating a generic training tool, it is also possible to integrate patient-specific imaging, enabling patient-specific procedure rehearsal. This could improve patient safety and be particularly useful for complex high-risk procedures (Willaert et al., 2010). For instance, in 2017, a surgeon and this team visualized VR models of the hearts of conjoined twins in order to prepare for the separation surgery. VR enabled them to discover a new connective tissue and made them change their operative strategy completely, leading to a successful surgery (Holley, 2017). The technology could even go further: VR might be used to perform remote surgeries, using remote-controlled robots (Deloitte, 2018a).

In addition to surgical training, research also focuses on the use of VR in **psychology and psychotherapy**, which results from its capability to simulate reality and to incur a high level of presence (Freeman et al., 2017). First, psychology research could benefit from VR because it allows a direct replication of studies, an experimental control of complex social situations, the creation of situations impossible to simulate in laboratory as well as a higher ecological validity, i.e. the extent to which the test performance predicts behaviours in real-world situations, than traditional studies (Pan & Hamilton, 2018). For similar reasons, VR shows great potential for the treatment of mental health disorders such as anxiety, schizophrenia, eating disorders, addiction and so on (Freeman et al., 2017). Most studies focus on anxiety disorders like phobias and post-traumatic stress disorder (PTSD) because VR can be a medium for exposure therapy, which is widely used to treat these disorders. It consists in confronting the patient with the feared stimuli (Riva, 2005) and using a therapist to guide him/her. A significant benefit of VR exposure therapy (VRET) is its greater user acceptance (Botella, Fernández-Álvarez, Guillén, García-Palacios, & Baños, 2017): participants feel safer because they know it is not real but their mind and body act as if it was (Freeman et al., 2017). Even if VRET is not significantly more efficient than exposure in real-life situations, evidence shows that it is effective and that its positive effects are generalized to real-life (Morina, Ijntema, Meyerbröker, & Emmelkamp 2015).

3.2.3 Secondary sector

The secondary sector can also take advantage of VR for its internal operations. The technology is used in diverse domains such as aerospace, energy and construction. In particular, the automotive industry uses VR to a large extent across several applications.

First of all, because VR enables users to view and interact with objects at true scale, it is especially relevant for **design purposes**, supporting the decision-making process (Berg & Vance, 2017; Michalos, Karvouniari, Dimitropoulos, Togias, & Makris, 2018). On the one hand, it can be used as a tool for *facility layout design*, which directly influences the productivity, the production costs but also the workers' physical fatigue (Michalos et al., 2018). For example, Ford was able to reduce the physical impact of assembly tasks on operators by using VR and motion sensors to analyse human movements and set design specifications (Berg & Vance, 2017). It resulted in a 70-percent decrease of employee injuries and an increased productivity (Capgemini, 2018). When optimizing shop floor layouts, VR makes it possible to evaluate how workers perform in a specific layout, to identify opportunities, to detect bottlenecks and to gather data without the need to implement full-size prototype, which is expensive and time-consuming (Michalos et al., 2018; Tyagi & Vadrevu, 2015). On the other hand, *product design and review* also highly benefit from the use of VR. For instance, visibility in a particular setting, reachability of product components as well as aesthetic qualities can be assessed in an immersive environment during vehicle prototyping. In the energy sector, abstract data such as wind wakes of turbines can be visualized and exploited to improve turbine design (Berg & Vance, 2017). Just as the physical design of a facility, a classical product design process is long and costly. Developing virtual prototypes instead of physical mock-ups is cheaper and shortens the development cycle. Furthermore, the design process often involves many reviews, errors and regular adjustments (Lawson, Salinitri & Waterfield; 2016). VR can perfectly tackle those issues thanks to its flexibility and reusability (Makris, Rentzos, Pintzos, Mavrikios, & Chryssolouris, 2012). Collaborative product design is another benefit of VR: multidisciplinary teams of experts can simultaneously access the same virtual design space and interact with the same prototype, no matter their location (Lawson et al., 2016; Makris et al., 2012). Implementing remote collaboration, Ford increased the efficiency of its design processes and cut travel costs (Capgemini, 2018).

This ability to interact remotely with an environment led to **teleoperation** applications. VR can be used as a human-machine interface for telerobotics. When there exists a barrier between the human operator and the environment, teleoperation can be the solution. For instance, this barrier could be a substance, e.g. hazardous materials, or a distance (Stoll, Wilde & Pong, 2009). For this reason, the main industries in the secondary sector that could benefit from teleoperation are energy and aerospace, for assembly and maintenance purposes. Autonomous robots can be of great help for some operations but cannot always be used because some tasks are too complex and some environments are not predictable enough (Chen et al., 2017). In those contexts, the intelligence and experience of humans are required to make quick and precise decisions (Rastogi & Kumar Srivastava, 2019). In order to create a real VR experience, the remote environment should be virtually reconstructed in 3D in real-time, a task that was investigated by Navarro, Fdez, Garzón, Roldán, & Barrientos (2015) and Cazamias & Raj (2016) among others. Some research also considers 360° camera recordings displayed in HMDs for VR teleoperation, such as in Linn et al. (2017) and Chen et al. (2017), and even if this does not correspond to the definition of virtual reality given in this thesis, it is worth mentioning. Haptic force feedback can be integrated to improve the performance of the human expert (Chen et al., 2017; Lederman & Taylor, 1969). Low latency communication between the VR environment and the real environment is an important requirement for a teleoperation system (Rastogi & Kumar Srivastava, 2019; Stoll et al., 2009). Moreover, different sensors can be placed in the involved environment to gather useful data that can be included in the virtual environment (Bonin-Font, Massot Campos & Burguera, 2018; Réalité-Virtuelle.com, 2018). As potential applications, Stoll et al. (2009) described the advantages of using VR for in-space robotic assembly, Bonin-Font et al. (2018) developed a platform enabling immersive teleoperation of underwater vehicles and Rastogi & Kumar Srivastava (2019) designed a control system for the remote maintenance of a nuclear fusion machine including haptic feedback. In any case, any teleoperation application of VR consists of a mix between the real world and virtual world. According to the *Reality-Virtuality Continuum* of Milgram & Kishino (1994) that has already been presented in this work, it is therefore mixed reality rather than virtual reality because the real augments the virtual through various sensors.

Finally, employee **training** is another common application of VR in the secondary sector. It can be applied to various practical skills, but it often involves assembly, maintenance or safety training. Using VR training instead of traditional training methods offers a wide range of benefits. First, through the increased engagement resulting from a learning by doing approach (Gavish et al., 2015), the retention of information is higher (Accenture, 2018; Lawson et al., 2016) and the knowledge transfer is more effective (Zawadzki, Buń & Górski, 2019). This higher effectiveness has been proven by analysing the number of errors, the number of attempts, the task completion time and the time taken to learn of VR training in comparison to conventional training (Accenture, 2018; Deloitte, 2018b; Langley et al., 2016; Zawadzki et al., 2019). Moreover, adding haptic feedback can improve the performance (Langley et al., 2016) Another important benefit of VR training is the fact that mistakes do not have real consequences for people's safety or for the equipment (Accenture, 2018), which is particularly interesting for safety training (Li, Yi, Chi, Wang, & Chan, 2018; Zhao & Lucas, 2015) and hazardous environments (Caporusso, Biasi, Cinquepalmi, & Bevilacqua, 2019; Naranjo, Ayala, Altamirano, Brito, & Garcia, 2018; Zio et al., 2019). Furthermore, VR training turns out to be more economic (Deloitte, 2018b; Gavish et al., 2015; Li et al., 2018; Zawadzki et al., 2019; Zio et al., 2019) because it is a cost-effective way to recreate real-life situations. For instance, ground staff can be trained in airplane docking without incurring logistics and fuel costs (Accenture, 2018). When it comes to safety training, the sense of presence induced by VR can help trainees relate to the risks involved, thanks to « *it can happen to you* » scenarios (Zhao & Lucas, 2015, p. 60). In addition, VR systems can easily track and gather data about the trainee and its performance, which can help the trainer to further analyse the execution (Gavish et al., 2015) and to provide tailored and individual feedbacks (Deloitte, 2018b). Additionally, the data can also be used by the management for better analytics (Accenture, 2018). VR training also has the advantage of being a flexible and adaptive solution. The experience can be adapted to the goals of the training and the needs of the worker (Gavish et al., 2015; Zawadzki et al., 2019; Zhao & Lucas, 2015). For example, the Volkswagen Group launched its Digital Reality Hub, a platform combining several VR applications related to production and logistics. This platform can be used for collaboration and design, but also for training (Volkswagen, 2017). The goal is to train 10,000 employees around the world (Immersive Learning News, 2018).

3.2.4 Tourism

VR has a great potential in different areas of tourism. Guttentag (2010) classified potential impacts of VR on tourism into six categories. First, **marketing and promotion** is probably the most researched application area. Given that tourism products are intangible (Griffin et al., 2017) and cannot be tried out in advance (Guttentag, 2010), a sensory experience such as VR can be a way to offer a “try before you buy experience” to prospective tourists (Tussyadiah, Wang, Jung, & tom Dieck, 2018). This would support their decision-making process (Huang, Backman, Backman, & Chang, 2016), reduce the perceived risk thanks to the rich data provided and also induce more realistic expectations (Griffin et al., 2017; Guttentag, 2010). Some research compared the impact of different kinds of visual promotional tools with VR. Griffin et al. (2017) found out that 360° video VR experiences produced more positive emotions and a higher probability to research information about the destination than traditional 2D videos or websites. In the context of hotel previews, Bogicevic, Seo, Kandampully, Liu, & Rudd (2019) studied the effects of VR on brand experience through the sense of presence, compared to less interactive 360° tours and static images. Results showed that VR enabled people to better project themselves in the services context and amplified brand experience. The influence of VR tourism experiences on the intention to visit a destination has also been researched. Tussyadiah et al. (2018) gave empirical evidence that the sense of presence created in VR had positive effects on attitude and behaviour, by shaping interest in the destination which in turn influenced visit intention. A study of Kim, Lee, & Jung (2018) revealed that cognitive and affective responses resulting from the perceived authenticity of a VR experience were factors predicting visit intention. For all those reasons, the tourism sector is adopting virtual tours and experiences as part of their promotional mix. For example, Thomas Cook and Virgin Holidays installed VR headsets in their stores to enable customers to experience different destinations through 360° videos, which resulted in a rise in sales and bookings for those destinations (Syahrin, 2017).

Then, **planning and management** could use VR to analyse and assess sites or activities that are still in development from different perspectives and with different settings, as a result of the visualization capabilities and the flexibility of VR (Guttentag, 2010). Another application area is **entertainment** because VR has the ability to enhance tourist attractions. For instance, several theme parks already offer VR experiences, such as Six Flags which has a roller coaster in which people wear VR headsets and experience a futuristic battle (Six Flags, 2016). Furthermore, **education** is the goal of some touristic activities, leading to edutainment, combining education and entertainment. As an illustration, The Natural History Museum of London launched an app which transports users to areas of the museum which are not accessible to visitors and gives them the opportunity to interact with priceless specimens, guided by a natural history expert (Pavid, 2018). This application is also linked to the two last areas of tourism impacted by VR, **accessibility** and **heritage preservation**. Accessibility can be restricted because the tourist site does not exist anymore or is too far, too fragile or too dangerous for example. Heritage tourism refers to activities related to places or artefacts that "*authentically represent the past*" (Bec et al., 2019, p. 188). VR can create substitutes for those inaccessible and historical sites/objects. To that end, 3D models of the real-world sites or objects are created, using most of the time laser scanning or photogrammetry, or reconstructed from archive repositories. As a result, one benefit is that sites threatened by the rise of their popularity could be preserved (Bec et al., 2019; Guttentag, 2010). An example of VR in heritage tourism is a Colosseum tour in VR in Rome, which immerses tourists in Ancient Rome in the days of gladiators (Ancient and Recent, n.d.).

3.2.5 Defence – Public safety

One of the first sectors to have invested in virtual reality is the military, and the technology is still considered as highly promising in the field. The army mainly uses VR for **training** because of its benefits over standard military exercises, whether for vehicle training or infantry training. A VR simulation is a time- and cost-effective alternative because it does not require to move soldiers to a foreign country nor to use expensive equipment and fuel in a physically simulated situation. It also enables to train soldiers in a risk-free environment, thus allowing to simulate any highly dangerous scenario (Fan & Wen, 2019; Koźlak, Kurzeja & Nawrat, 2013; Lele, 2013; Liu, Zhang, Hou, & Wang, 2018). However, soldiers think they are in a life-threatening situation through the sense of presence. This is critical if their behaviour and decision-making process in stressful situations need to be analysed. Furthermore, different scenarios can be easily implemented, and soldiers can train for the exact same mission several times (Koźlak et al., 2013; Lele, 2013). The performance of the troops can then be analysed by the instructors thanks to a digital playback of the simulation, which also serves as a tool for after action review (AAR) and feedback (Fan & Wen, 2019; Koźlak et al., 2013). For instance, the U.S. army started using VR for infantry training purposes in 2012 with the *Dismounted Soldier Training System* (DSTS) (U.S. Army, 2012): soldiers are equipped with HMDs, special suits and simulated rifles, and the squad trains for real-life combat scenarios in a virtual space (Fan & Wen, 2019). This leads to cheaper, faster and more efficient training (WatchTheDaily, 2012). More recently, both the U.S. and the British Army invested in cutting-edge VR training programmes (Bohemia Interactive Simulations, 2019; Dormehl, 2019). The sector of public safety can also benefit from the use of immersive VR in their training activities for the same reasons as the army. Williams-Bell et al. (2015) reviewed virtual simulations that might be used for training in the fire service. For safety and cost reasons, more and more fire departments invest in VR equipment (Haymond, 2019). As for the police, the New-York Police Department is currently assessing the use of VR training for real-life scenarios (Roston, 2019).

Using VR in **teleoperation** also makes sense for the military. Telerobotics are commonly used for highly dangerous operations, but also when physical deployment of troops is impossible. For now, mobile robots are controlled thanks to data received from sensors and cameras. However, for complex tasks, VR could be a more intuitive and more efficient control system (Kot & Novák, 2018).

3.2.6 Financial services

Research on the use of VR in the finance sector is almost non-existent. The only relevant paper that could be found concerns stock trading visualization. The goal of VR in this context is to enhance the working environment of traders by presenting abstract data in a virtual environment rather than on several monitors (Rumiński, Maik, & Walczak, 2018). This can help to get a better understanding (Moran, Gadepally, Hubbell, & Kepner 2015). Moreover, VR can be an opportunity to promote remote collaboration (Rumiński et al., 2018). Some companies identified the same applications as the literature, along with other potential applications. For instance, Salesforce created a tool to enable companies to analyse data in an immersive 3D environment with a VR headset (Salesforce, n.d.). The CEO of Virtualitics, a company combining Big Data, artificial intelligence and VR, suggests that visualizing data in VR can provide useful insights to financial companies (Amori, 2017). Furthermore, banks and financial institutions are developing VR apps to help clients manage their accounts and their stock portfolio in a simpler way thanks to virtual agents and visualization tools (BNP Paribas, 2017; CREALOGIX Group, 2017; Schouela, 2018).

3.2.7 Applications classified by business function

To summarise the applications presented in the subsections above, the categorisation criteria is no longer the sector but the business function. The objective is to present the different applications from another perspective. This classification is presented in Table 3.1. It should be noted that the secondary sector mostly encompasses the automotive, energy, construction and aerospace industries.

Business function	Application(s)	Main sector(s) concerned
Human Resource Management	Training	• Healthcare • Defence • Public safety • Secondary sector
Sales and Marketing	• Customer experience • Promotion • Market research	• Retail • Real estate • Tourism • Financial services
Research & Development	• Product design and review • Remote collaboration	Secondary sector
Production/Operations	• Teleoperation (i.e. assembly and maintenance) • Patient treatments	• Secondary sector • Defence • Healthcare
Supply Chain Management	Facility layout design	Secondary sector
Finance and administration	• Data visualization • Remote collaboration	Financial services

Table 3.1: Main applications of VR classified by business function

According to a survey of PwC (2016), the most common application of VR in the US manufacturing industry in 2016 was product design and review (38%), followed by skills training (28%) and remote collaboration (19%). As for the industries, the biggest investor in VR technologies is the automotive industry, followed by retail and healthcare (PwC, 2017). As for the scientific literature, a recent systematic review of immersive technologies found out that most research papers concern education, healthcare, entertainment and marketing (Suh & Prophet, 2018).

3.3 IMMERSION AND PRESENCE

The concepts of immersion and presence have already been introduced when defining virtual reality and its key components. However, as already mentioned, there exist different definitions and points of view about these terms in the literature. The goal of this section is to describe these different approaches, the factors influencing immersion and presence, as well as diverse techniques to measure them. Finally, some existing studies are presented.

3.3.1 Immersion

There are two school of thoughts when it comes to immersion. The first one, used previously in section 2.2.1, directly links immersion to the technical characteristics of the technology. This implies that immersion is objective (Miller & Bugnariu, 2016; Sanchez-Vives & Slater, 2005; Slater & Wilbur, 1997). The more the tracking and sensory modalities (vision, hearing, touch, smell, taste) provided by the system are faithful to their corresponding sensory modalities in the real world, the more the system is considered as immersive (Slater, 2003).

Slater & Wilbur (1997) identified several characteristics of the system which positively influence the level of immersion, as represented in Figure 3.1. First, the inclusiveness, which refers to how much the user is isolated from physical reality. Ideally, there should not by any interference from the physical world. Then, the vividness, representing the fidelity, resolution and richness of each sensory modality. The extensiveness, which corresponds to the scope of sensory modalities supported. Proprioceptive matching is also a key component to immersion: the user's proprioception, the "*perception or awareness of the position and movement of its body*" ("Proprioception," n.d.), must match the received sensory data. Besides, a self-representation in the virtual environment through a virtual body is necessary. Moreover, if the system delivers a surrounding illusion of reality, meaning a panoramic field of view, the immersion increases. Finally, Slater & Wilbur (1997) suggest that the degree to which the virtual environment is a self-sufficient world in which the user can actively take part also affects immersion.

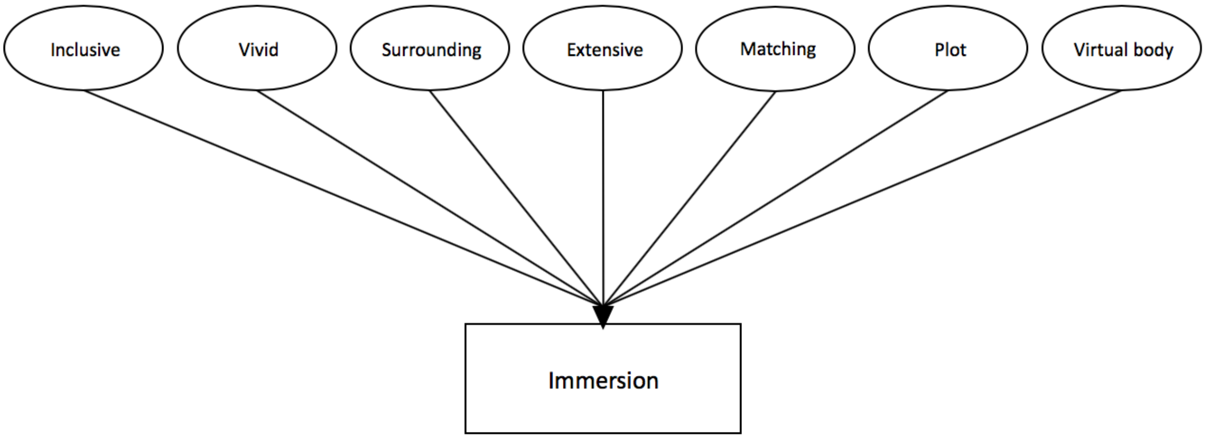


Figure 3.1: Characteristics of the system influencing the level of immersion from Slater & Wilbur (1997)

The second school of thought defines immersion as "*a psychological state characterized by perceiving oneself to be enveloped by, included in, and interacting with an environment that provides a continuous stream of stimuli and experiences*" (Witmer & Singer, 1998, p. 227). The notion of perception appearing in this definition is the main divergence of the two approaches. In this case, immersion is linked to an experience rather than objective technical characteristics, even if the equipment configuration is considered as part of the factors inducing immersion. For instance, in their factors affecting immersion, Witmer & Singer (1998) include natural modes of interaction and control, along with components corresponding to the inclusiveness and proprioceptive matching described by Slater & Wilbur (1997). Nevertheless, individual factors of the user are taken into account in this point of view, such as concentration, involvement and ability to adapt to the virtual environment (Witmer, Jerome & Singer, 2005).

In spite of their slightly different perspectives on the definition of immersion, both approaches agree on the fact that the higher the immersion level, the higher the presence level (Slater & Wilbur, 1997; Witmer & Singer, 1998). To understand how presence is affected by immersion, the concept of presence must be defined.

3.3.2 Presence

Overall, all authors concur that presence is the psychological sense of being in an environment and is positively influenced by the level of immersion. It is the fact that the simulated environment prevails over the actual physical surroundings (Slater & Wilbur, 1997; Steuer, 1992; Witmer & Singer, 1998). Nonetheless, presence is a "*multifaceted concept*" (Witmer & Singer, 1998, p.239) and the factors inducing presence can differ from one author to another.

The first approach presented is the one of Slater. Slater & Wilbur (1997) suggest that the relationship between the immersion level and presence is not direct. The impact of all aspects of immersion on presence is subject to two filters: the sensory requirements of the specific task to be accomplished and the personal perceptual needs of the user. This means that although Slater & Wilbur (1997) consider immersion as objective, a subjective filter is applied to immersion in the context of its influence on presence. Moreover, presence can be decomposed in an objective and a subjective component (Slater & Wilbur, 1997). The subjective component corresponds to the "*suspension of disbelief*" (Slater & Wilbur, 1997, p.606), the illusion of being there as reported by the user. This can be referred to as Place Illusion (PI). PI highly depends on sensorimotor contingencies (SCs), the set of actions that generate changes in the virtual environment but also in the participant's perception. The supported SCs define some elements of the immersion of a system, which in turn determine limits within which PI can arise. If these SCs are similar to those of physical reality, PI can occur. The objective component of presence is the realistic behaviour of the user in the virtual environment. In other words, the user responds to situations and events in a similar way as he/she would in a comparable context in real life. This is enabled by PI on the one hand, and by Plausibility Illusion (Psi) on the other hand. Psi corresponds to the overall credibility of the events occurring in the environment. If events which are not caused by the participant refer directly to him/her and if they conform to expectations, then Psi increases (Slater, 2009). As a result, presence is more likely to be maintained over time (Slater, Lotto, Arnold, & Sanchez-Vives, 2009). In this first approach, some factors are not considered relevant to create presence: high fidelity visual realism is not essential according to some studies (Usoh, Catena, Arman, & Slater, 2000; Zimmons & Panter, 2003), neither are emotional content, involvement and engagement (Slater et al., 2009).

On the contrary, the second approach holds that involvement is a key factor inducing presence (Schubert, Friedmann, & Regenbrecht, 2001; Witmer & Singer, 1998; Witmer et al., 2005). Involvement is a psychological state resulting from selective attention. Selective attention refers to a certain focus on consistent stimuli rather than unrelated ones. In the case of a VR experience, the consistent stimuli come from the virtual environment and the unrelated ones from the physical world. Involvement is also positively influenced by the extent to which activities are stimulating and engaging. As already mentioned, immersion is another factor contributing to presence. Concentration positively influences involvement and immersion, probably explaining why involvement and immersion are correlated. However, the ability to adapt to the environment appears to be more essential to immersion than concentration (Witmer et al., 2005). Globally, Witmer et al. (2005) identified 4 factors leading to presence. In increasing order of explanatory power of presence, those factors are: Involvement, Sensory Fidelity (including visual, auditory and haptic elements), Adaptation/Immersion and Interface Quality (quality of the visual and control interfaces). Even if those factors are all required for a multidimensional measure of presence, some of them are significantly correlated. All relationships between the elements presented in this paragraph are summarized in Figure 3.2 and Figure 3.3.

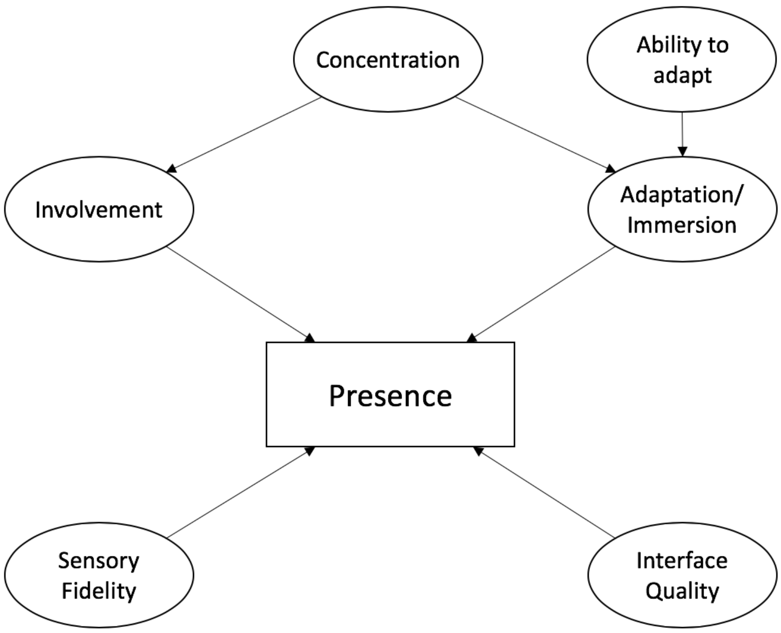
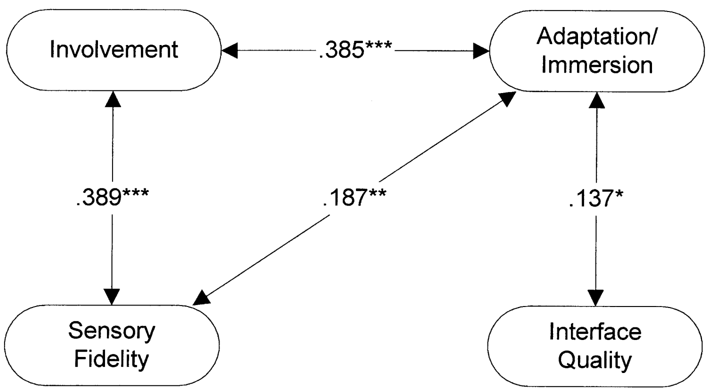


Figure 3.2: Elements influencing presence from the 4-fator analysis from Witmer et al. (2005)



Note: * = p<.01, ** = p<.001, *** = p<.001

Figure 3.3 : Presence Questionnaire: between-factor correlations (reprinted from Witmer et al., 2005, p. 308)

Just as the first two approaches, the last approach presented considers that the level of presence depends on the characteristics of both the virtual environment and the individual (Slater, 2009; Steuer, 1992; Witmer & Singer, 1998). The technological variables influencing presence (corresponding to telepresence from the point of view of Steuer (1992)) can be divided in 2 two categories: vividness, corresponding to the sensory richness, and interactivity. A factor directly contributing to vividness is the number of sensory modalities that are simultaneously activated, the sensory breadth. The information redundancy detected by the different perceptual systems enhances vividness. The quality of the information provided to the perceptual systems, called the sensory depth, also strengthens vividness. As for interactivity, influencing factors are the following: response time of the environment to inputs, number of attributes that can be modified, and mapping of real actions to virtual actions. Although these technical characteristics are objective, their relative influence on the sense of presence varies across individuals, as depicted in Figure 3.4. Moreover, the circumstances of the virtual simulation, its context, can affect the relative importance of the different sensory modalities for the individual. Personal concerns also have a key role in determining the level of presence (Steuer, 1992). Overall, the point of view of Steuer (1992) is quite close from the one of Slater & Wilbur (1997), with Steuer's technological variables corresponding to the characteristics of the immersion level. Nevertheless, as opposed to the approach of Slater (2009) but in accordance with the approach of Witmer et al. (2005), Steuer (1992) suggests that engagement induces presence. Engagement helps the user to create a first-order relationship with the virtual environment, which encourages presence.

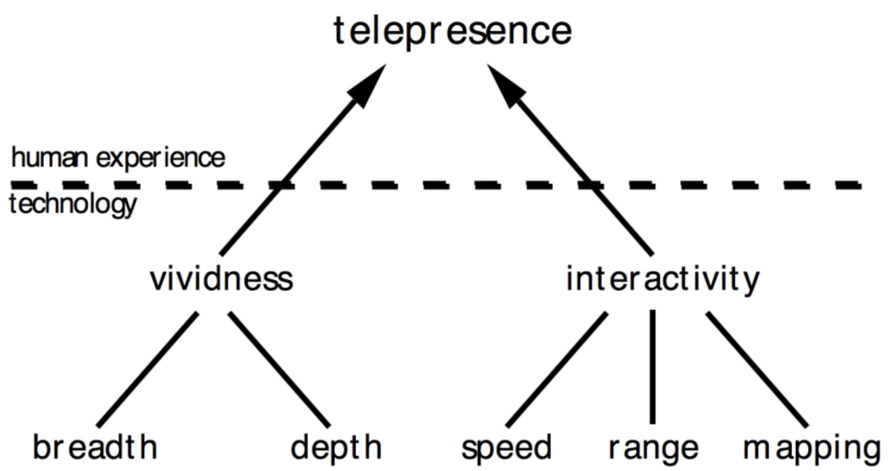


Figure 3.4: Technological variables influencing presence (reprinted from Steuer, 1992, p.81)

3.3.3 Measuring presence

Given that the sense of presence has both a subjective and an objective component, there is no perfect method to measure it. However, several methods exist.

The most common method to measure presence are post-experience questionnaires (Ochs, Jain, & Blache, 2018). Participants accomplish some tasks in the virtual environment before answering subjective questions about their perception of the environment (Garau et al., 2008; Slater et al., 2009). Several questionnaires have been designed but the four most renowned are the Presence Questionnaire (PQ) of Witmer & Singer (1998), the Slater-Usoh-Steed (SUS) questionnaire (Usoh et al., 2000), the IGroup Presence Questionnaire (IPQ) of Schubert et al. (2001) and the ITC-Sense of Presence Inventory (ITC-SOPI) of Lessiter, Freeman, Keogh, & Davidoff (2001). These questionnaires are statistically significant to test presence (Ochs et al., 2018). Apart from the SUS questionnaire, all of them were developed from a principal-components factor analysis. Although questionnaires are easy to use, one of their main problem is that prior information can influence the outcome, making them unstable (Freeman, Avons, Pearson, & Ijsselsteijn, 1999). Moreover, the concepts used in the questions are vague and subject to interpretation (Slater, 2004).

To tackle the subjectivity problem of questionnaires, behavioural and physiological approaches can be used because a highly present user acts and responds realistically (Slater, 2009). Behavioural measures require a bodily response from the participant, which can be caused by specific stimuli. For instance, a postural shift can be measured (Sanchez-Vives & Slater, 2005). The drawbacks of this method are its content-dependency limitation (Garau et al., 2008) and the potential subjectivity of the experimenter when determining if the response was caused by the experiment (Insko, 2003). The same goes for physiological measures, i.e. heart rate and skin temperature.

Another possible approach consists in retrieving breaks in presence (BIPs) experienced by the participant during the VR exposure and deducting a measure of presence from those BIPs (Slater & Steed, 2000). A BIP can be defined as "*any perceived phenomenon during the VE exposure that launches the participant into awareness of the real-world setting of the experience*" (Slater et al., 2009, p. 205). For example, bumping into a wall in the physical world when there is no wall in the virtual world can create a BIP. There exists a stochastic model to estimate a measure of presence from BIPs and it has been proven that this estimator is positively correlated with usual questionnaire measures (Slater & Steed, 2000).

New methods are currently being developed and analysed. For instance, Ochs et al. (2018) created a machine-learning method able to automatically predict the sense of presence of a participant after its VR experience, relying on multimodal behavioural measures. The advantage of this approach is its objectivity.

3.3.4 Previous studies

Many studies were carried out in the context of immersion and presence. Display parameters such as graphics frame rate, head-tracking, field of view and stereopsis are positively correlated with presence (Barfield, Baird & Bjorneseth, 1998; Barfield & Hendrix, 1995; Hendrix & Barfield, 1996a; Ijsselsteijn, De Ridder, Freeman, Avons, & Bouwhuis, 2001). Sound is also a determinant of the sense of presence, with spatialized sound being the best sound setting (Hendrix & Barfield, 1996b). Furthermore, haptic feedback (Basdogan, Ho, Srinivasan, & Slater, 2000; Kim, Jeon & Kim, 2017; Meehan, Insko, Whitton, & Brooks, 2002) and fidelity of interaction (Barfield et al., 1998; Hendrix & Barfield, 1996a) induce a higher level of presence. Some studies also compared the presence level of different VR systems. The results show that HMDs and CAVEs create a higher presence level than desktop systems (Buttussi & Chittaro, 2018; Kim, Rosenthal, Zielinski, & Brady, 2014; Korber, Kurzmann & Neuper, 2012; Settgast, Pirker, Lontschar, Maggale, & Gütl, 2016).

However, there is no study comparing the immersion and presence levels of different hand tracking technologies in the literature. For this reason, the comparative study presented in Chapter 5 focuses on a comparison between the Leap Motion, an infrared camera, and a VR data glove.

Chapter 4: Case Study

In order to illustrate the applications of virtual reality to the corporate world, a business case study is carried out. This case study demonstrates that companies turn to virtual reality to meet their operational needs. The case study concerns the aviation industry and its training procedures. Its goal is to determine if virtual reality is a potential useful tool for pilot training and if it feasible from a technical point of view. To begin with, the company which encounters a business problem is briefly presented. The source of the problem as well as the VR solution chosen by the company to solve it are described. Then, a market research of flight simulators is carried out to assess the potential of the solution, but also to identify prospective competitors. In section 4.3, the proof of concept developed for the company is described. Different immersive technologies have been implemented in order to maximise the level of immersion. They are analysed in the last section of this chapter.

4.1 PRESENTATION OF THE CASE

The case study of this thesis is focuses on training procedures for pilots at ASL Airlines Belgium (ASLB). This company is a Belgian cargo airline based in Liège Airport. Formerly TNT Airways, it was the airline of the TNT group until it was acquired by ASL Aviation Holdings in 2016. ASL Airlines Belgium operates worldwide with its own fleet under the ASL brand but also works for major express integrator customers. Its customers also include freight forwarders and companies with demand for air cargo solutions (ASL Airlines Belgium, 2018). The fleet includes 33 freighters overall, among which B737, B747 and B757 (Plane Spotters, 2019). It operates scheduled flights mostly in Europe (more than sixty destinations) but also to Asia, Middle East and America. Chartered flights and ACMI (Aircraft, Crew, Maintenance, Insurance) to other air carriers are also part of ASL Airlines Belgium's operations (ASL Airlines Belgium, n.d.). Its parent company, ASL Aviation Group, has a portfolio of nine other airlines and operates on 6 continents (ASL Aviation Holdings, 2017).

In the aviation industry, future pilots must go through different levels of simulation during their training before flying a real aircraft, and experienced pilots must train regularly. ASL Airlines Belgium mostly uses cockpit procedures trainers to train their pilots. Those cockpit procedures trainers consist of large printed pictures of the cockpit, as shown in Figure 4.1. The apprentices must show the buttons to be used during the procedure. This method is not sufficiently realistic for the training.

Figure 4.1: Cockpit procedures trainer (reprinted from https://www.simfly.com.au/cockpit-procedure-trainers/)

There exist more immersive simulators, but they are expensive and ASL Airlines Belgium does not own one. Therefore, their pilots must often go to Brussels or abroad in order to train properly. Taking into account the trip, those pilots might be unavailable for the operations for 2 or 3 days, which represents an opportunity cost. This solution is unpractical and expensive; indeed, pilots have to be replaced when they go training, which means that more staff is required.

To tackle the problem, ASL Airlines Belgium decided to work with the HEC Digital Lab, a transdisciplinary centre that leads state-of-the-art research and education in digital technologies applied to the corporate world. The goal of this partnership is to develop an immersive flight simulator in virtual reality, which can be used to train pilots in the different preflight, inflight and postflight procedures. For the proof of concept, the simulated aircraft is a Boeing 737, the most common freighter in the fleet of ASLB. The benefits of using virtual reality for training have been proven and the technology has been used to that end in some industries for years.

4.2 MARKET RESEARCH: FLIGHT SIMULATORS

When developing a new solution, the starting point is to analyse the market. In order to carry out this market research, it is important to start by determining the reference market. To that end, the first step is to define the customer need, which is the need to simulate a real flight in this case. Then, the currently available solutions for that need must be identified. When it comes to flight simulators, these solutions can be divided into three different categories. First, the most advanced flight simulators are called Full Flight Simulators (FFS). An FFS corresponds to a full-size replica of an aircraft cockpit, including all equipment and computer programmes required for flight and ground operations. Moreover, as shown in Figure 4.2, a realistic force cueing motion system is included (European Aviation Safety Agency, 2012).

Figure 4.2: Full flight simulator (reprinted from https://www.cae.com/civil-aviation/airlines-fleet-operators/training-equipment/full-flight-simulators/)

A system with similar characteristics but without a motion system is called a Fixed-Base Simulator (FBS) or flight training device and is depicted in Figure 4.3.

Figure 4.3: Fixed-base simulator (reprinted from https://www.virtualaviation.co.uk/self-fly-hire)

Finally, the last type of flight simulators simply consists of a software and will be referred to as desktop flight simulator. Additional hardware, such as rudder pedals or a yoke, can sometimes be added.

FFSs and FBSs are professional simulators. They are mostly used by airlines and flight schools, even if some companies also offer flying activities in simulators to the general public. However, according to some studies, an FFS does not help to improve performance during training, even for manoeuvres that should theoretically require motion cues (Aviation Focus, 2018; Bürki-Cohen, Sparko, & Go, 2007; Sparko, Bürki-Cohen, & Go, 2010). For this reason, FFSs and FBSs are considered as a whole in this market research, referred to as complete simulators. Even if an FBS is cheaper than an FFS, both those simulators can cost millions of dollars. This is the reason why ASL Airlines Belgium does not want to invest in such systems and intends to develop a more affordable solution. Although a VR flight simulator might seem costly, it is by far less expensive than complete simulators. Furthermore, a VR simulator is a portable system that can easily be deployed in several locations without further costs, apart from the costs of the hardware.

There exist many desktop flight simulators. These systems represent the direct competitors of the product ASL wants to develop because a VR flight simulator is a type of desktop simulator. Consequently, the following subsection is dedicated to a competitive analysis of desktop flight simulators.

4.2.1 Competitive analysis of desktop flight simulators

Because of the large amount of desktop flight simulators, it is not possible to analyse all of them. To select which simulators to analyse in detail, some criteria must be defined. First, combat flight simulators were excluded of the analysis because civil aviation and military aviation are two different fields. Thus, target customers of combat flight simulators do not look for the same features as those of civil flight simulators. Then, the main flight simulators on the market were selected based on online research. Websites, forums and articles were skimmed, and six simulators were chosen for the competitive analysis: X-Plane 11, Prepar3D, Microsoft Flight Simulator X, Aerofly FS2, FlyInside and FlightGear.

An important feature to consider is the possibility to use a virtual reality mode. Indeed, simulators including a VR mode are the most significant competitors for the product

ASLB wants to develop because they use the same technology. Among the selected flight simulators, X-Plane 11, P3D, Aerofly FS2 and FlyInside support native VR. All of them work with both the Oculus Rift and the HTC Vive as a headset, but P3D does not support VR controllers for interaction with the cockpit. Additionally, FlyInside supports the Leap Motion, enabling the user to directly use his/her own hands in the cockpit. FSX does not have a VR mode but FlyInside created a VR add-on for FSX. As for FlightGear, it does not include a VR mode. For this reason, this free flight simulator is not analysed more deeply. The five remaining flight simulators are presented hereunder.

FlyInside is an under-development flight simulator, already available in early access on Steam for 30.99€. This price is going to increase with further development. Unlike the others, this simulator is specifically built for VR, even if it can also be played on desktop. For now, ten aircraft are available, including a B737-200. The company claims that its simulator will always reach 90 frames per second (fps) and that it outperforms other simulators on that aspect (FlyInside, 2018b). It is meant to be open platform and a scripting SDK is provided to help developers to create add-ons. Moreover, FlyInside offers custom solutions and support for commercial and research activities (FlyInside, 2018a). A flight school is also in development and includes at the moment one tutorial about basic controls and one tutorial for a B737 start-up procedure with a checklist. A multiplayer mode is provided but does not allow several players in the same cockpit. In the settings, different flight modes can be selected: easy, medium, realistic. Furthermore, FlyInside works with Go Touch VR, a French company developing haptics solutions for virtual training, in order to give pilots a touch-based confirmation of their actions in the cockpit (Adams, 2018).

AeroFly FS2 is a flight simulator targeting the global market and is sold for 59.99€ on Steam. Its strengths are a high performance in VR resulting in smooth frame rates, as well as the high-quality graphics of planes and scenery. However, according to the reviews, it does not seem to provide a realistic flight experience for all types of aircraft because systems are simplified. Some controls are not interactive or just do not have noticeable effects (Anderson, 2018; Steam, n.d-a). There is no multiplayer mode, but it is possible to get a simulated co-pilot that can help with controls. Twenty aircraft are included, among which a B737-500. Flight lessons are available, but they focus on basic manoeuvres for the Cessna 172 and only involve a few controls. It is possible to create airports, aircraft and scenery with the SDK (Aerofly, 2019).

Microsoft Flight Simulator X (FSX) is the last version of the most famous flight simulator in the world, Microsoft Flight Simulator. FSX targets the general public and is beginner-friendly. Out of the box, the aerodynamics is not very realistic because FSX uses tables or approximated values to compute them. However, the biggest asset of the software is probably the large number of existing add-ons, and some of these add-ons can improve the aerodynamics. For instance, there is a B737-800 in the basic FSX but a much more realistic model with also higher system fidelity can be bought: PMDG 737NGX 800/900 is an officially licensed product of Boeing and was developed with technical input from Boeing. It costs 60€ and can be extended with PMDG 737-600/700 for an extra 23.34€ (PMDG, 2019). With FSX, it is possible to share the cockpit with another player in the multiplayer mode. Moreover, a learning centre provides written flying lessons about different airplanes, which can then be put in practice in the simulator. FSX is available on Steam for 24.99€ since 2014. Nevertheless, this flight simulator is older than that because it was first released in 2006. Although some features were modified between 2006 and 2014, there is not a big difference between the two versions. Furthermore, there has not been much further development since 2014 and bugs are frequent because FSX is a 32-bit architecture (Fly Away Simulation, 2019; Steam, n.d.-b)

Lockheed Martin **Prepar3D** (P3D) is a simulation software intended for pilots, militaries, academia and commercial organizations. Thus, rather than a game, it is a professional simulator for training, simulation and learning (Prepa3D, 2019). For example, P3D is used as flight simulator software by TRC Simulators for its fixed-base simulators (Prepar3D, n.d.). Different license options are offered. The basic professional license costs 199$ and the developer license can be acquired for 9.95$ per month. In its developer version, P3D features an intuitive training and simulation scenario generation tool, as well as a virtual instructor (Prepa3D, 2019). However, flight and procedure tutorials are not included. Nevertheless, a flight instructor add-on called FSFlyingSchool including various flying lessons on different aircraft can be bought for 40$ (also available for FSX and X-Plane 11) (http://www.fsflyingschool.com/). Just as the other flight simulators presented in this subsection, there exists an SDK enabling developers to create various add-ons such as aircraft, scenery and missions. Moreover, some add-ons for FSX are also compatible with P3D. There is no B737 among the default aircraft but for 90$, the PMDG 737NGX package is also available for P3D. In a multiplayer session, two users can be in the same cockpit. Although both pilots can operate aircraft systems and radio simultaneously, only one pilot can fly the aircraft at a time, but aircraft control can be transferred to the other pilot at any time (Prepar3D, 2015). As already mentioned, VR controllers are not supported in P3D. To interact with the cockpit controls, there are two options: the mouse can be directly used or gaze selection with head movements can control the mouse. Regarding performance in VR, a quite powerful machine is required, and some settings might have to be adjusted to get an acceptable performance. Furthermore, the amount and type of add-ons also affect the fps.

The last flight simulator of this competitive analysis is **X-Plane 11**. It is developed by Laminar Research, a software company which puts emphasis on accurately reflecting the laws of physics. Therefore, X-Plane uses *blade element theory* for aerodynamics, an engineering process "*breaking the aircraft down into many small elements and then finding the forces on each little element many times per second*" (X-Plane, 2019b, para. 1). X-Plane claims that this flight model is the only one able to simulate how aircraft fly, and that X-Plane 11 is not a game (Digital Trends, 2019). Indeed, there exists a professional use version of the software with advanced features. This professional version costs 750$ (per computer) instead of 60$ for the regular version on Steam. Yet, the professional version is a certified software of the Federal Aviation Administration (FAA) of the United States. However, it is only possible to get an FAA-certification for a flight training system combining certified software and certified hardware. The hardware required can cost hundreds of thousands of dollars (X-Plane, 2019a). X-Plane 11 is able to simulate system failures and bad weather conditions. Besides, it supports plug-ins, aircraft and scenery add-ons, and provides development tools and a Plugin SDK. The default fleet encompasses about ten aircraft, among which a B737-800. It is not directly possible to share the aircraft with another pilot but there exists a plug-in, SmartCopilot, that enables it (Sky4Crew, n.d.). A flight school with basic lessons on a Cessna 172 is included. Just as for P3D, some rendering settings might have to be adjusted to reach a sufficient performance in VR, depending on the machine utilized.

In order to easily compare the different features of the presented flight simulators, a summary is provided in Table 4.1.

	X-Plane 11	P3D	FlyInside	Aerofly FS2	FSX
VR	Native	Native	Native	Native	Using FlyInside plug-in (29$)
Positioning	Professional	Training, simulation and learning	Global market	Global market	Global market
Shared cockpit	With SmartCopilot Plug-in	Yes	No	No	Yes
Flight school	Basics (Cessna 172)	Via FS Flying School	•Basics (B55) •Procedures (B737)	Basics (Cessna 172)	Various lessons (several aircrafts)
Add-ons	•Aircraft models •Scenery •Plug-ins	•Aircraft •Scenery •Missions •…	Various add-ons	•Airports •Aircraft •Scenery	Various add-ons
B737	B737-800 included	Via PMDG 737 NGX (90$)	B737-200 included	B737-500 included	B737-800 included but PMDG 737 NGX available (±60€)
Price	•Regular: 60$ •Pro: 750$	•Basic: 199$ •Developer: 9,95$ per month	31€ (early access)	60€	25€
Miscellaneous	FAA-certified professional version	SimDirector for scenario generation	•High performance in VR •Leap Motion support	High performance in VR	Very large number of add-ons

Table 4.1: Features summary of the main desktop flight simulators

After analysing these five flight simulators, it is important to consider the point of view of the customers ASLB wants to target with its product. The target customers are airlines and training centres for pilots. This customer segment looks for features different from those sought by gamers and flight simulator enthusiasts. Accurate aerodynamics and high system fidelity are essential features of a flight simulator used by this segment. This flight simulator must also be reliable. Moreover, when it comes to training, pilots should be able to practice different scenarios and to be guided by instructions if necessary. It can be concluded that in this context, FSX and Aerofly FS2 are not major competitors for ASLB because they do not target the same segment. Aerofly FS2 is more considered as a casual flight simulator than a realistic flight simulator and thus, is not suitable for professional simulation. As for FSX, it is old and outdated, which makes it not reliable enough for training activities. FlyInside is not ruled out at this point because on the one hand, their positioning strategy is not clear and on the other hand, the software is still in under development.

4.2.2 Competitive advantage of ASL Airlines Belgium

The three most significant competitors identified in this competitive analysis are therefore X-Plane 11, Prepar3D and FlyInside. The competitive advantage of the flight simulator ASLB plans to develop must now be identified. Two types of competitive advantage exist: cost advantage and differentiation advantage. A cost advantage is the result of a cost leadership strategy, whereas a differentiation advantage consists in offering a unique product with distinctive qualities which can thus be sold at a higher price. As a new entrant on the flight simulator market, ASLB would struggle with a cost leadership strategy because it requires a higher productivity than the competitors for a similar product, and this is not likely to happen. However, ASLB's product could differentiate itself on specific features. Thus, a differentiation strategy is the best choice for ASLB.

From the competitive analysis, it can be deduced that each of the three main competitors have their own specific strengths. X-Plane 11 is very realistic, Prepar3D is designed for training, and FlyInside is specifically built for VR. The product of ASLB can be seen as a combination of these strengths in a single product. First, the objective is to create a flight simulator which is extremely faithful to reality, especially in terms of system fidelity, thanks to the help of technical pilots. Second, this flight simulator is only meant to be used for pilots training activities. Therefore, an emphasis on the educational aspect of the simulator is essential in the differentiation strategy. To that end, a multiplayer mode allowing the instructor to join the pilot in the virtual cockpit is an added value. Finally, these two first characteristics will be combined with VR, a technology able to create immersion. To reinforce the level of immersion, different immersive technologies can be used. Moreover, given that there does not exist a patent for an immersive virtual reality flight simulator yet, it is a great opportunity for ASLB to patent the invention and to highlight this point when commercializing it.

Before developing the complete flight simulator and eventually commercializing it, a proof of concept must be developed to assess the feasibility of the project and its potential. As an intern at the HEC Digital Lab, I had the opportunity to lead this project. The goal was to develop a realistic VR flight simulator for the preflight procedure of a B737. A description of this proof of concept and its development is provided in the next section.

4.3 FLIGHT SIMULATOR PROOF OF CONCEPT

The first step of a virtual reality project is to create the **3D model** of the virtual environment. The 3D model of the cockpit was designed using a poster as a reference for the equipment. Following a presentation of the under-development proof of concept to a technical pilot, corrections were made to the dimensions and to some controls. The final result is depicted in Figure 4.4 and additional visuals can be found in Appendix A.

Figure 4.4: Overview of the virtual cockpit

Once the virtual environment modelled, **interactions** can be implemented. The first thing to consider when working on interactions is how to give the ability to interact with the virtual environment to the user. The easiest solution is to use the controllers associated with the VR headset, which is the HTC Vive for this proof of concept. However, the goal of the VR cockpit is to be as immersive as possible and using these controllers to interact with the control panels is not close enough to reality. For this reason, two different types of technologies enabling to match the virtual hands to the real physical hands of the user have been implemented: the Leap Motion and VR gloves. Their respective specificities are presented in section 4.4. In order to increase the level of immersion, a pilot character was modelled. Its arms follow the virtual hands and its head is linked to the headset.

The next essential component of interactions is the set of objects that can be interacted with. In the case of a cockpit, these objects are mainly the controls that are dispersed all over the cockpit. Even though there is a large number of controls, most of them can be classified into four categories: switches, buttons, knobs and levers, as shown in Figure 4.5. The interaction with one type of control was implemented once and then deployed for all controls of the same type. However, a few settings had to be adjusted individually for each control, such as the number of different positions of switches, the default position of a switch in case it is guarded, the allowed rotation of knobs and levers as well as the pressure range of buttons.

Figure 4.5: Types of controls. From left to right: switches, button, knob and lever

Apart from those controls, a very important part of a cockpit is the yoke. It is different from a lever because it is composed of two parts, each one having its own rotation axis. Moreover, the yoke must come back to its initial position when released. Rudder pedals are another system used to control the movement of the aircraft. Because feet are not tracked like hands, a set of physical pedals is used to control the virtual rudder pedals. The yoke and the pedals, shown in Figure 4.6, serve as inputs for a motion seat, another immersive technology presented in section 4.4.

Figure 4.6: Yoke and pedals

All interactions have been implemented to be as natural as possible in the way they are performed by the users. Nevertheless, there is an exception. There exist different types of switches and one of them requires the pilot to first pull the switch before moving it, in order to unlock it. Because it is quite difficult to detect if the pilot pulls the switch, the solution implemented is to click on the switch to unlock it, resulting in the switch coming out of the panel as if it was pulled. Afterwards, the switch can be interacted with.

As already mentioned, the possibility to use the virtual cockpit on a **network** is an asset for educational purposes. This would enable several pilots to join the same virtual environment and to interact with each other. It means that the instructor could sit next to the trainee and give him/her additional information if necessary, or even show the trainee manoeuvres. This could be particularly useful if the instructor and the trainee are not in the same city or country because the distance would not be an obstacle anymore.

Finally, to train pilots in the **preflight procedure**, the sequence of steps to be completed by the pilot should be programmed. A generic tool has been implemented to create a sequence. Pedagogically-speaking, the final version of the flight simulator should include three different modes: a learning mode, a testing mode and a crash mode. The goal of the learning mode is to help and guide the trainee throughout the whole procedure thanks to indications such as a halo surrounding the control to be interacted with and a text specifying the correct value, as shown in Figure 4.7. As for the testing mode, it does not include any indication, but it informs the trainee that he/she made a mistake when necessary. This mode could also include a counter for mistakes in order to provide the trainee with a concrete feedback. Finally, the crash mode is specifically designed for unusual situations. Problems and complications can be introduced in the environment in order to teach trainees specific emergency procedures and related counteractions. For the proof of concept, only the learning mode has been implemented.

Figure 4.7: Overview of the learning mode

Any VR project requires 4 categories of expertise: a computer graphics artist to model the virtual environment, a programmer to implement interactions, a project manager to coordinate the team and to set the objectives, and a technical expert in the field of the application to provide additional useful insight. The staff costs to develop this proof of concept with such a team amount approximately to 42,500€ for twenty weeks of full-time work.

4.4 IMMERSIVE TECHNOLOGIES

Several immersive technologies were used in order to provide the highest level of immersion possible to the flight simulator. Each following subsection describes one particular approach.

4.4.1 Leap Motion

The Leap Motion controller is composed of infrared cameras that track the hands of the user as well as their gestures. It can be mounted directly on the VR headset, as shown in Figure 4.8. It enables the user to simply move its real hands and see its virtual hands in the cockpit moving accordingly. Hand gestures are detected with high accuracy and very low latency is achieved. Moreover, it is easy to set up, easy to use and not cumbersome. It costs approximately 100€.

Figure 4.8: Left, Leap Motion mounted on the HTC Vive headset. Right, virtual hands from the Leap Motion

However, the Leap Motion is not perfect for several reasons. First, the main problem of the Leap Motion is that the hands need to be in the field of view of the user to be detected. For example, this could be problematic if the pilot wanted to hold the yoke and look at the overhead panel at the same time. Second, it is quite sensitive to the lighting so it can happen that it fails to detect the hands, which impedes the experience. Finally, it does not allow for haptic feedbacks when touching objects, which decreases the immersion level. Nonetheless, the Leap Motion does not require much equipment and is very practical for demonstrations.

4.4.2 VR gloves

All VR gloves have different specifications. One of the most important features of a VR glove is the technology used to track the hand and fingers. There exist two different technologies for the fingers: flex sensors and IMU (Inertial Measurement Unit) sensors.

Flex sensors analyse the resistance of the sensor, which is directly proportional to the amount of the bend. Thus, gloves with flex sensors in the fingers, as shown in Figure 4.9, can measure the bend of the finger joints and bend the fingers of the virtual hands accordingly.

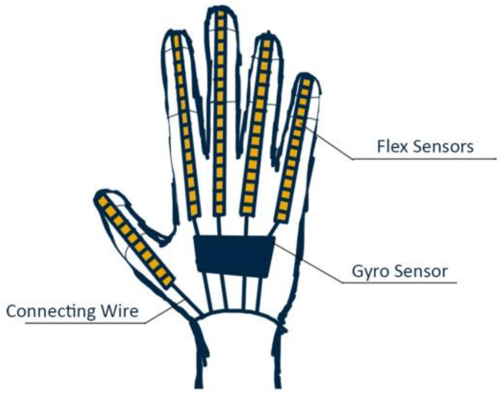


Figure 4.9: Glove with flex sensors (reprinted from http://blog.ocad.ca/wordpress/gdes3015-fw201503-01/category/speculative-wearables)

On the other hand, an IMU measures angular rate, force and sometimes magnetic field. Therefore, the main difference between flex sensors and IMUs is that IMUs are able to measure all movements of the fingers, not only the bend. Movements recognized by IMUs but not by flex sensors are shown in Figure 4.10.

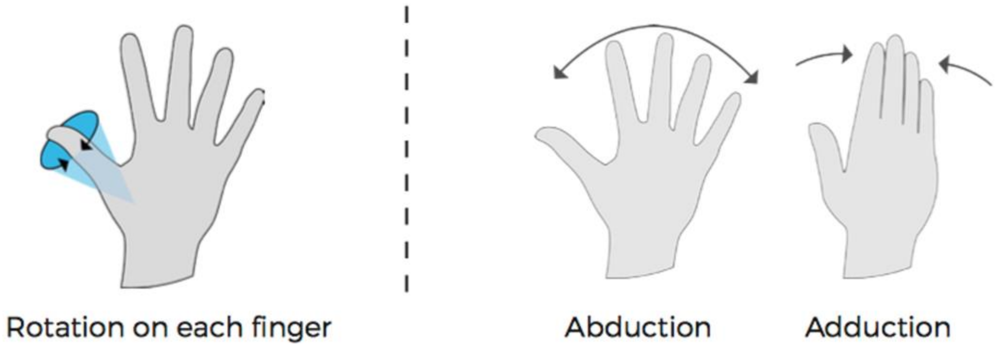


Figure 4.10: Movements which can be identified only by IMUs (reprinted from NeuroDigital, 2018, p. 2)

The latency of the gloves, so the delay between the moment the user moves its hand/finger and the moment the virtual hand reacts, is also very important because it is critical for a seamless experience.

On the flight simulator proof of concept, I worked with 3 different gloves: first the GloveOne by NeuroDigital, then the Avatar VR by NeuroDigital, and finally the Hi5 VR Glove by Noitom. Another VR glove, the CaptoGlove, was tested by my predecessor at the HEC Digital Lab. It was rapidly discarded because of its high latency and thus, is not further analysed in this thesis.

The GloveOne is equipped with haptic actuators and conductive surfaces for gesture recognition. To enable positional tracking, the position of the hands must be manually programmed to follow HTC Vive trackers. Its main weakness is its finger tracking technology: using flex sensors instead of IMUs, full finger tracking cannot be achieved (Neurodigital, 2017). In fact, NeuroDigital removed the GloveOne of its product offerings, meaning that developing the VR cockpit based on the GloveOne was not a good idea anymore because ASL Airlines Belgium could not have bought the gloves for their training activities once the application is ready.

For those reasons, we ordered the Avatar VR. With this new glove, NeuroDigital achieved full finger tracking with IMUs. The latency depends on the communication system used, USB or Bluetooth, but is satisfactory in both cases. It is however quite expensive because a yearly license is required to have access to the SDK and API, but also to make the gloves compatible with the VR headset (NeuroDigital, 2018; NeuroDigital, n.d.).

Consequently, after some research online, the Hi5 VR Glove seemed to be a good alternative; its finger and hand tracking is as good as the one of the Avatar VR and its price is much lower. Moreover, it is compatible with the HTC Vive trackers, both from a software and hardware perspective. Indeed, it is equipped with a mounting surface for trackers and programmed to directly use the tracking data, which makes positional tracking easier than with the gloves of NeuroDigital. Its latency might be higher than the one of the USB-connected Avatar VR, but it is lower than the wireless Avatar VR. In comparison to gloves developed by NeuroDigital, it does not include haptic feedbacks for each fingertip. Instead, vibrations on the wrists can be enabled. Thus, the biggest shortcoming of this glove is its low level of haptic feedbacks (Noitom, 2019).

The specifications of all the presented gloves are summarized in Table 4.2.

	CaptoGlove	*GloveOne*	*Avatar VR*	*Hi5 VR Glove*
Finger tracking	Flex sensors	Flex sensors	6 IMUs (9-axis)	7 IMUs (9-axis)
Hand tracking	One 9-axis IMU	One 9-axis IMU	One 9-axis IMU	One 9-axis IMU
Positional tracking	/	/	/	Compatible with *HTC Vive* trackers
Communicati on	Bluetooth	USB and Bluetooth modes	USB and Bluetooth modes	Wireless through dongle
Haptics	/	10 actuators (fingertips/palm) with different levels of intensity	10 actuators (fingertips/palm) with 1024 levels of intensity	One vibrator on the wrist
Latency	High	USB: Ultra low Bluetooth: Low	USB: 1 ms Bluetooth: < 8ms	< 5 ms
Price	450€ for the pair	499€ per glove	License 2,500€ per year + 799€ for one glove / 1499€ for the pair	999$ for the pair (excluding VAT)
Miscellaneous	/	Contact areas for gesture recognition	Contact areas for gesture recognition	Replaceable AA battery

Table 4.2: Specifications of the VR gloves

There are further VR gloves on the market, e.g. ManusVR, HaptX and Plexus, but I only considered the gloves I had the opportunity to test in this analysis.

VR gloves are an interesting alternative to the Leap Motion because they can solve all the problems related to the Leap Motion. Moreover, they might be more precise for some kinds of interaction. Nonetheless, VR gloves also have their faults. They require a setup, they are cumbersome and finger tracking can sometimes have problems. As part of this thesis, a study comparing both technologies was carried out. In addition to contributing to research, it can help to determine which one is the best choice for the flight simulator. This is the topic of next chapter. However, the pros and cons of the Leap Motion along with those of the final VR glove selected for the proof of concept, namely the Hi5 VR Glove, are already presented in Table 4.3.

	Leap Motion	*Hi5 VR Glove*
Pros	• Practical • Cheap (± 100€) • Accurate when the hand is clearly visible	• More precise for knobs • Tracked whatever the spatial position of the hand • Accurate when no bug
Cons	• Limited field of view of the camera • Lighting-sensitive • Difficulty detecting a closed hand (especially problematic for knobs)	• Expensive (Gloves + Trackers = ± 1,250€) • Tracking problems sometimes • Requires setup and calibration • Different sizes • Fragile • Hygiene

Table 4.3: Pros and cons of the Leap Motion and the Hi5 VR Glove

4.4.3 VRtouch

If the hand tracking system does not include any haptic feedback, a solution can be to clip small haptic devices on the fingertips, called VRtouch. This solution is developed by Go Touch VR, a company creating haptic solutions for business. It is recommended to wear 3 devices per hand, as show in Figure 4.11. Each device includes an actuator applying pressure on the fingertips to simulate contacts. The actuator can either close itself completely, which is suitable when holding controls in the aircraft, or simply vibrate, which is suitable for short contacts. This has been implemented in the proof of concept, but it would be worthwhile to further improve the haptic feedback. However, the real question is whether haptic feedbacks actually make the experience more immersive when interacting with the cockpit controls. This topic goes beyond the scope of this thesis.

Figure 4.11: VRtouch wearable haptic devices (reprinted from https://www.gotouchvr.com/copy-of-technology-devices-1)

4.4.4 Motion seat

As the aircraft is eventually going to fly, increasing the level of immersion can probably be achieved by making the body of the user follow the movements of the aircraft. To that end, we can use a two-degree-of-freedom motion seat. However, the relationship between the use of the motion seat and the level of immersion should be empirically tested before making any conclusion. This seat has to be configured to move according to the inputs coming from the yoke, pedals and levers. The programmer working with me on the project was responsible for the motion of the seat. He managed to make the seat move according to the movements of the yoke but also according to the inputs of the pedals. This is a first step towards an immersive inflight experience. The aircraft can also approximately takeoff and fly, but without realistic aerodynamics. Nevertheless, as the preflight procedure does not require any movement of the aircraft, this is not crucial to the proof of concept.

Chapter 5: Comparative study on immersion

The developed proof of concept presented in the previous chapter has two purposes. Obviously, its primary goal is to meet the need for a training system of ASL Airlines Belgium. However, the flight simulator environment was also developed for research purposes. In this chapter, a study comparing two different immersive technologies for hand tracking in virtual reality, the Leap Motion and the Hi5 VR Glove, is presented. Moreover, this study will also benefit ASLB because the findings can guide the choice of the interaction system for the flight simulator proof of concept. First, the chosen methodology is described. Then, different types of results are analysed. Finally, the limitations of this comparative study are determined.

5.1 METHODOLOGY

This section is divided into four subsections. First of all, the aim of the study is presented, along with a description of the experimental approach utilized. Next, an insight into the characteristics of the participants is provided. Finally, the materials used to gather relevant data are explained, as well as the experimental procedure.

5.1.1 Purpose and experimental design

The goal of this comparative study is to determine whether the use of VR gloves provides a different level of immersion and presence than the Leap Motion. The gloves used for this study are the Hi5 VR Gloves presented in the previous chapter. Furthermore, the ease of interaction with the environment and the precision of both technologies are compared. It is assumed that a difference exists between the two immersive technologies, but the direction of this difference is unknown. Thus, bilateral tests must be used. The immersive technology is the categorical independent variable of the study. Its value is either Leap Motion (LM), or VR Glove (G).

To carry out a study, different types of experimental designs can be used, each of them having its pros and cons. For this study, two experimental designs were considered: within-subject design (WSD) and between-subject design (BSD). The WSD was chosen, also known as repeated measures. It means that each participant will experience both experimental conditions, each condition corresponding to a different immersive technology in this case. The main advantage of this method is that it requires half as many participants as BSD because they take part in both experiments. Due to time limitations, this characteristic was decisive for the choice of the method. Moreover, each participant is used as his/her own control and the internal validity is not linked to random assignment to groups (Charness, Gneezy, & Kuhn, 2012). Nonetheless, WSD is not perfect. On the one hand, *demand effects* can occur, meaning that the judgement of the participants is influenced by their interpretation of the researcher's intentions, based on the variation of the independent variable. On the other hand, order effects can exist, which in this case would be *practice effects*. Indeed, participants will be asked to perform a similar task in the same environment twice and thus, their second performance will be impacted. Luckily, these familiarisation effects can be reduced thanks to counterbalancing (Mullet & Chasseigne, 2018): half of the participants will start with the Leap Motion as hand tracking system, and the other half will start with the Hi5 VR Gloves.

This study encompasses two experiments per participant. In both cases, the virtual environment used is the B737 cockpit developed for ASLB. The participant has the role of a pilot executing the preflight procedure. The real preflight procedure of a B737 could not be used because it is too long and too complex for such an experiment. Furthermore, two different procedures had to be designed in order to avoid practice effects. This prevents the participant from anticipating the sequence of actions and, as a consequence, completing the procedure faster. Each procedure is assigned to one immersive technology. Nevertheless, to be able to compare the results of both experiments, the proportion of each different type of control used in the procedure should remain the same. Therefore, each sequence contains twelve switches, five knobs, four buttons and five levers. The microphone, the parking brake and the yoke are also involved in the procedures, resulting in a total of thirty interactions per experiment. To indicate to the participant which control must be interacted with at each step of a procedure, the learning mode of the developed flight simulator, presented in section 4.3, is used. Thus, a halo appears around the relevant control, along with a text specifying the instructions. Once the correct value is set, the halo and the text move on to the next control. However, no instruction is provided when the participant enters the cockpit; for twenty seconds, he/she can simply look around the cockpit to adapt to the virtual environment. An audio recording notifies the participant when the preflight procedure starts.

Before going to the cockpit, the participant must learn how to interact with the different types of controls present in the virtual environment. This prevents participants from wasting time trying to understand by themselves the interaction mechanisms. For this reason, a tutorial in a distinct virtual environment was designed. As shown in Figure 5.1, it consists of a panel comprising one example of each main type of controls, namely switches, knobs, buttons and levers. The tutorial works exactly as the learning mode of the cockpit, except that the instructions appear on a fixed panel. The participant interacts with each control once during the tutorial but is free to try out all controls as many times as he/she wants before going to the cockpit. The tutorial is included in all experiments, no matter if it is the first or second session of the participant, and no matter the technology. Although interaction mechanisms are the same for both hand tracking systems, it is important to let the participant get used to the new virtual hands at the beginning of each experiment, to avoid skewing the results.

Figure 5.1: Tutorial environment

5.1.2 Participants

For this study, 17 participants were recruited. They were evenly split into two experimental groups. Group A consists of participants who used the Leap Motion during the first experiment and group B consists of participants who started with the Hi5 VR Gloves. Group A includes 9 participants (4 males, 5 females) and the other 8 participants were assigned to group B (4 males, 4 females). Groups are balanced in terms of gender. All participants are between 18 and 25 years old. Around 59% of the participants had already experienced VR formerly, 23.5% of them belonging to Group A and 35.3% to group B. Six participants have already been in a cockpit, but only two of them remember it clearly and none of them was familiar with the controls. Because most interactions in the virtual cockpit require to use the right hand, the handedness of the participants might matter. Only 2 participants were left-handed and both of them belong to group B.

5.1.3 Measurements

This subsection briefly describes the instruments used for data collection. Quantitative methods are mostly used, especially questionnaires. A copy of each questionnaire can be found in the Appendices from page 91.

The first questionnaire is the **Immersive Tendencies Questionnaire (ITQ)** of Witmer and Singer (1998). As its name suggests, it measures the "*capability or tendency of individuals to be involved or immersed*" (Witmer & Singer, 1998, p. 230). A significant positive correlation exists between the ITQ score and the sense of presence. The questionnaire is composed of 18 items. Each item is rated on a seven-point Likert scale, with two opposing descriptors at the ends and a midpoint anchor (Witmer & Singer, 1998). However, the experiment is carried out in French because it is assumed to be the mother tongue of most, if not all, participants, and this questionnaire is in English. For this reason, a validated French adaptation from the Cyberpsychology Lab of the UQO is used (Cronbach's alpha = 0.78, N=94). In this case study, this test is only used to make sure that participants have a sufficient immersive tendency. If the score of a participant on the ITQ is lower than the mean provided by the Cyberpsychology Lab by more than one standard deviation, the participant will not be included in the analysis.

To measure presence, a French adaptation of the **Presence Questionnaire** (Witmer et al., 2005) already introduced in sections 3.3.2 and 3.3.3 is used **(Questionnaire sur l'état de présence, QEP)** (Cronbach's alpha 0.84, N=101). Just as for the ITQ, each item is assessed using a seven-point scale format. Instead of the four subscales identified by Witmer et al. (2005), the French version comprises five subscales. "Realism" refers to the similarity between the virtual environment and an equivalent physical environment. "Affordance to Act" corresponds to the ability to actively explore and interact with the virtual environment. "Interface Quality" deals with delays or difficulty linked to the software or equipment. "Affordance to Examine" refers to the ability to approach and examine virtual objects. Finally, "Self-assessment of Performance" concerns the feeling of proficiency to accomplish tasks (Robillard, Bouchard, Fournier, & Renaud, 2003). This results in a total of 19 items.

In addition to presence and immersion measurements, more detailed information about the hand tracking technologies should be collected. Thus, a short questionnaire specific to the virtual hands was designed with the help of a postdoctoral researcher in psychology. It is referred to as **Hand Questionnaire (HQ)**. It is composed of 4 items which are rated based on a continuous scale from 0 to 10. The items cover spatial tracking, ease of interaction, fluidity and precision.

Because the results given by all these questionnaires are only based on self-report information, a more objective measure is necessary. Therefore, the amount of time required to complete the entire preflight procedure is computed for each experimental session. The timer starts when the first instruction appears and stops when the participant accomplishes the last step of the sequence. This measure is referred to as **Time to Completion (TTC)**.

A **cybersickness questionnaire** is also filled out by the participants. The questionnaire is the French version of the Simulator Sickness Questionnaire of Kennedy, Lane, Berbaum, & Lilienthal (1993). It enables to check if a low score on the QEP and/or the HQ results from adverse effects of VR or from the hand tracking technology itself.

5.1.4 Proceedings

As already stated, two experimental sessions are required for each participant, one for each immersive technology to be tested. First of all, during the first session, an informative document is provided to the participant and a consent form must be filled out. Then, the participant answers the ITQ and the cybersickness questionnaire. It is also asked if the participant has already experienced VR and been in a cockpit. Subsequently, the tasks to be completed in the virtual environment are explained. Even if the tutorial will describe the interaction mechanisms, the different types of controls and the most efficient way to interact with them are verbally presented before the immersion, in order to maximize information retention. Afterwards comes the immersion phase which starts with the tutorial and is followed by the fulfilment of the preflight procedure in the virtual cockpit environment. If the hand tracking technology to be tested is the VR gloves, the participant is equipped with the gloves before going in the virtual environment. The immersion phase is monitored on a display by the experimenter. During the tutorial, additional advice is given verbally to guide the participant. On the other hand, during the preflight procedure, the experimenter provides assistance only if the participant is struggling with a control. Throughout the entire immersion phase, the participant remains seated. Once the immersion phase is over, the participant directly fills out the QEP, the HQ and the cybersickness questionnaire. This concludes the first experimental session.

The second experimental session takes place one day or two days later in order to prevent contamination effects. Indeed, for repeated measures in the exact same environment, spacing out the experimental sessions reduces the impact of one session on the other. The pre-immersion phase simply consists in completing the cybersickness questionnaire. The immersion phase differs solely in the hand tracking technology used and the sequence of actions in the procedure. The same post-immersion questionnaires are filled out, namely the QEP, the HQ and the cybersickness questionnaire. Finally, to conclude the experiment, the participant is invited to openly comment about both hand tracking technologies and his/her preference. The goal of the study is then clearly explained.

5.2 RESULTS

The results of the comparative study are analysed in this section. All participants were used for this analysis because all scores of the ITQ were higher than the mean provided by the Cyberpsychology Lab for the questionnaire minus the standard deviation. First, the global results are presented, without any distinction between the groups related to the order. Then, a comparison between group A and group B is made in order to analyse the effect of the order on the data. The preferences of the participants are also investigated. Lastly, the performance of the proof of concept in terms of presence and interactions is evaluated.

5.2.1 Comparison of presence between both immersive technologies

The hypothesis of this test is that there is a difference in terms of presence between the Leap Motion (LM) and the Hi5 VR Glove (G). However, because the direction of the difference is undetermined, the following bilateral test is used: $H_0 : \mu_{LM} = \mu_G$ with $\alpha = 0.05$. A paired samples Student's t-test, appropriate for WSD, is chosen. The dependent variables used to measure presence are different scores from the QEP. It should be noted that the auditory subscale is not part of this analysis because the virtual environment was exactly the same for both experimental sessions. Therefore, any variation of the auditory score from one session to another can only come from a different judgement of the participant and is not relevant in this case.

First, the total score of the QEP is tested. This score measures the overall sense of presence of the VR experience. In Table 5.1, basic descriptive statistics are presented. As it can be seen, the mean of the QEP for the VR gloves is slightly higher than the one of the LM.

	Mean	SD	SE
QEP LM	104.9	12.12	2.940
QEP G	107.4	14.38	3.488

Table 5.1: Descriptive statistics of QEP for each immersive technology

To determine if the difference between the mean values is significant, the results of the paired samples t-test, available in Table 5.2, must be analysed. The high p-value proves that there is no significant difference between the level of presence provided by each hand tracking technology. It means that H_0 cannot be rejected and thus, that the sense of presence is similar in both cases. Cohen's d, measuring the effect size, can be considered as small.

	t	df	p	Cohen's d
QEP G - QEP LM	0.686	16	0.503	0.166

Table 5.2: Paired Samples T-Test for presence: G vs. LM

In order to get more insight about how the hand tracking technology influenced the total QEP score, the subscales can be used. The descriptive statistics for each subscale and each technology can be found in Appendix I. Table 5.3 encompasses the results of the t-tests run for each subscale. Nevertheless, three of the five subscales are more interesting to analyse than others, namely Affordance to Act (ACT), Interface Quality (IQ) and Self-assessment of performance (PERF). At least 50% of the items of these subscales are considered as dependent on the hand tracking technology rather than on the virtual environment itself. None of these t-tests is significant and H_0 cannot be rejected. However, the relatively higher effect size for the ACT and PERF subscales could be sign that with a larger population, the score of these subscales might be significantly higher for the VR gloves than for the Leap Motion.

			t	df	p	Cohen's d
REAL_G	-	REAL_LM	-0.673	16	0.510	-0.163
ACT_G	-	ACT_LM	1.603	16	0.129	0.389
IQ_G	-	IQ_LM	0.554	16	0.587	0.134
EXA_G	-	EXA_LM	0.922	16	0.370	0.224
PERF_G	-	PERF_LM	1.553	16	0.140	0.377

Table 5.3: Paired Samples T-Test for subscales of presence: G vs. LM

5.2.2 Comparison of technology capabilities between both immersive technologies

Apart from the sense of presence, it is also important to assess which technology is the most suitable and reliable to interact with the virtual cockpit. Technology capabilities encompass characteristics specific to the immersive technology used to represent hands in the virtual environment. The hypothesis in this case is that one technology provides more accurate hand tracking and interactions. The bilateral test is exactly the same as for presence: $H_0 : \mu_{LM} = \mu_G$ with $\alpha = 0.05$. The dependent variables correspond to scores from the HQ.

Once again, the total score of the HQ is analysed first in order to give a general overview. In Table 5.4, descriptive statistics are listed. Unlike the results of the QEP, the mean score of the HQ is slightly higher for the LM this time.

	Mean	SD	SE
HQ LM	28.218	5.993	1.454
HQ G	28.006	7.247	1.758

Table 5.4: Descriptive statistics of HQ for each immersive technology

Notwithstanding, this difference is once more not significant, as shown in Table 5.5. The p-value is extremely high, and the effect size is very small.

	t	df	p	Cohen's d
HQ G - HQ LM	- 0.107	16	0.916	- 0.026

Table 5.5: Paired Samples T-Test for technology capabilities: G vs. LM

To give a more detailed analysis, a paired samples t-test was performed for each item of HQ. The results are presented in Table 5.6. None of the items leads to a significant difference in terms of score between the different immersive technologies and Cohen's d values are small. It can be concluded that neither spatial tracking, nor ease of interaction, not fluidity, nor precision are significantly influenced by the hand tracking technology. Thus, H_0 cannot be rejected and the capabilities of both technologies are considered as similar. The corresponding descriptive statistics for each item can be found in Appendix I.

			t	df	p	Cohen's d
HQ1_G	-	HQ1_LM	-0.832	16	0.418	-0.202
HQ2_G	-	HQ2_LM	0.422	16	0.678	0.102
HQ3_G	-	HQ3_LM	0.513	16	0.615	0.124
HQ4_G	-	HQ4_LM	-0.389	16	0.702	-0.094

Table 5.6: Paired Samples T-Test for all items of HQ: G vs. LM

5.2.3 Comparison of performance between both immersive technologies

The most objective measure of performance available is the TTC. It is assumed that the faster the participant completes the preflight procedure, the more the hand tracking technology is convenient for interactions. A bilateral paired samples Student's t-test is also used for this analysis.

The average TTC for the VR glove is one minute shorter than for the LM. It should be noted that the standard deviation is quite high for both technologies. The units used in Table 5.7 are seconds.

	Mean	SD	SE
TTC_LM	358.1	122.5	29.71
TTC_G	298.6	123.8	30.03

Table 5.7: Descriptive statistics of TTC (in seconds) for each immersive technology

As it can be seen in Table 5.8, even this objective measure does not result in a significant difference between the immersive technologies. These results support those presented for presence and technology capabilities: the hand tracking technology does not significantly affect presence or user experience. However, the magnitude of the effect size suggests that a study with a larger population might give significant results.

	t	df	p	Cohen's d
TTC G - TTC LM	- 1.494	16	0.155	- 0.362

Table 5.8: Paired Samples T-Test for performance: G vs. LM

5.2.4 Comparison between group A and group B

For this subsection, the statistical model used is a two-way repeated measures ANOVA. This model is suitable comparison of means between groups. In this case, it is a 2 by 2 analysis of variance, with the group (A or B) as between-group factor and the immersive technology (LM or G) as repeated measures factor. The aim is to determine if an interaction between these two factors on a defined dependent variable exists. Furthermore, it enables to check if the results are different between groups. Two tests were carried out, each with a different dependent variable. These variables are the total scores of the QEP and HQ.

First, the marginal means are analysed using boxplots, but tables with the corresponding data can be found in Appendix J. The green lines represent the marginal means. Red dots correspond to participants of group A and thus started with the LM. Blue dots correspond to participants from group B, who started with G. As it can be seen in Figure 5.2, all measures improved from the first to the second session, no matter the group. This was expected because of practice effects occurring with repeated measures. It proves that it was important to use counterbalancing to get a reliable comparison. Furthermore, the mean for QEP with LM is almost the same for both groups, whereas the mean for QEP with G are quite different. This can also be observed for HQ, but it is less visible.

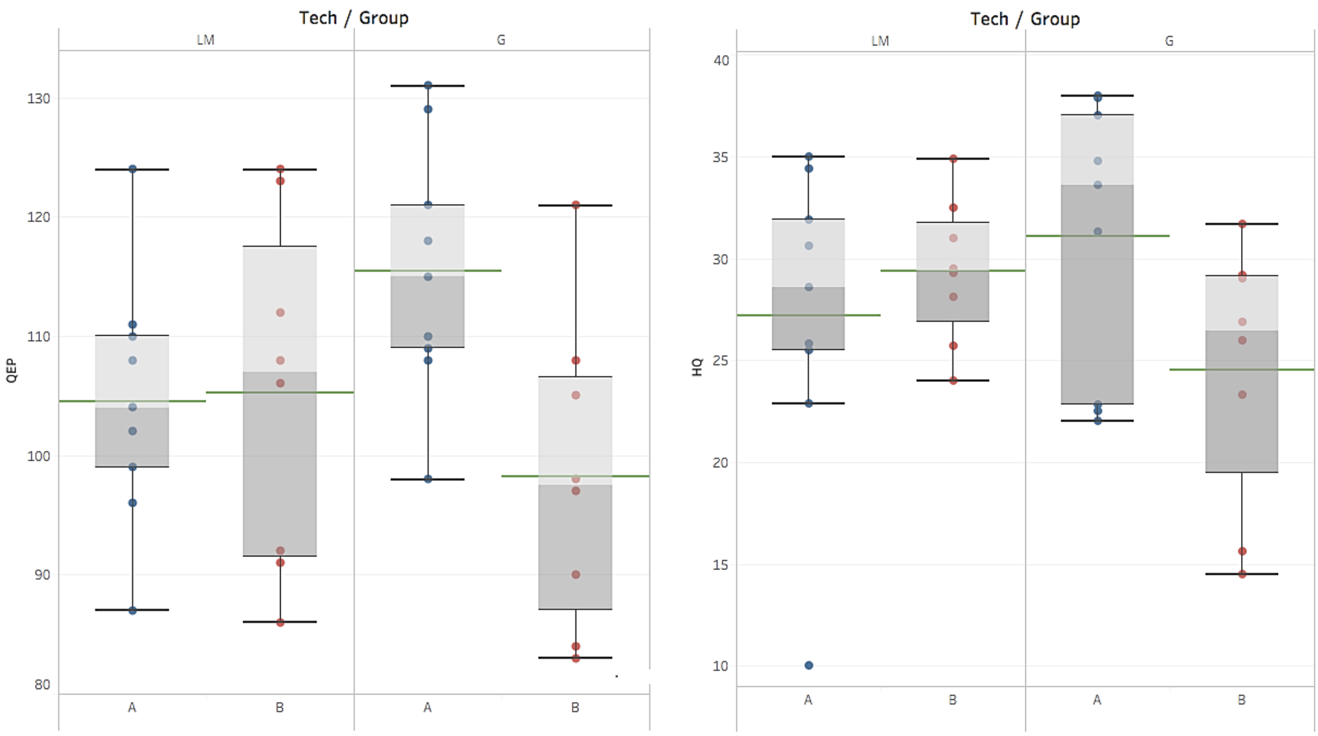


Figure 5.2: Boxplots of marginal statistics, for QEP on the left and for HQ on the right

To determine if the impact of the order on the results is significant, the output of the two-way repeated measures ANOVA must be analysed. Table 5.9 encompasses the results for both dependent variables. It appears that the order effect is not significant for any of the dependent variables. However, there is a statistically significant interaction between the group and the hand tracking technology, meaning that the effect of one of these variables on the score changes depending on the level of the other one.

Dependent variable	Effect	F	p	Partial eta-squared
QEP	Group	2.604	0.13	0.15
	Tech_used	0.442	0.52	0.02
	Tech_used*Group	9.356	*0.008*	0.384
HQ	Group	0.72	0.41	0.05
	Tech_used	0.08	0.79	0.005
	Tech_used*Group	6.66	*0.02*	0.31

Table 5.9: Two-way repeated measures ANOVA for QEP and HQ

To go further, Tukey's HSD (honest significant difference) test can be used. It evaluates whether the difference between a pair of means is significant. Results show that it is only the case for the difference between the presence scores of the VR gloves of group A and group B. Therefore, the order solely significantly affects the QEP score of the gloves, as already suggested by the box plots.

Dependent variable	Group	Technology used		{1}	{2}	{3}	{4}
QEP	A	LM	{1}	/	0.07	1	0.71
		G	{2}	0.07	/	0.33	*0.03*
	B	LM	{3}	1	0.33	/	0.38
		G	{4}	0.71	*0.03*	0.38	/
HQ	A	LM	{1}	/	0.37	0.89	0.82
		G	{2}	0.37	/	0.94	0.17
	B	LM	{3}	0.89	0.94	/	0.24
		G	{4}	0.82	0.17	0.24	/

Table 5.10: Tukey's HSD for QEP and HQ

5.2.5 Preferences of the participants

According to the participants, both technologies have their own advantages and disadvantages. The main reported benefits of the Leap Motion are its practical aspect as well as its hand and finger tracking. Its biggest reported problem is by far the interaction with knobs: almost all participants encountered difficulties when turning knobs, especially those requiring a precise value. As for the VR gloves, their main asset is a higher accuracy for precise interactions such as turning knobs. However, six participants experienced inaccurate hand and/or finger tracking with the gloves, which is the most considerable drawback of this technology.

In order to get additional information about the user experience potential of each immersive technology, participants were asked to choose the one they preferred overall. Seven participants stated that they preferred the Hi5 VR Glove to the Leap Motion. This represents approximately 41% of the participants. However, when looking at each group separately, it seems that the order influenced the final choice. Indeed, Table 5.11 shows that participants tend to choose the second technology, no matter the group.

	Preference		
Group	G	LM	Row Total
A	6	3	9
% within column	85.7%	30%	
B	1	7	8
% within column	14.3%	70%	
Total	7	10	17

Table 5.11: Contingency table Group(2) x Preference(2)

To define if the variables Group and Preference are independent or not, the Chi-square must be computed. Fisher's Exact Test is used to evaluate significance because it is suitable for two by two contingency tables with few observations. As it can be seen in Table 5.12, the significant p-value confirms that Group and Preference are dependent.

	Yates Chi-square	p	df
Fisher exact, one-sided	3.14	0.036	1

Table 5.12: Independence Fisher exact test for contingency table Group x Preference

It should be noted that although seven participants preferred the VR gloves, four of them considered that they were not worth the investment. Once the prices of each technology revealed, these participants felt that the difference in terms of performance and presence was not large enough to account for the large price difference between the Leap Motion and the VR gloves.

5.2.6 Performance of the proof of concept

The results of this comparative study can also be used to analyse the performance and the quality of the proof of concept developed for ASL Airlines Belgium. To that end, performance scores were computed for several aspects of the QEP and the HQ with the following formula:

$$Performance\ score\ = \frac{Mean\ score\ computed\ by\ the\ questionnaire}{Maximum\ score\ possible}$$

Different performance levels were defined arbitrarily. Over 80%, the performance is considered as high. Between 70% and 80%, the performance is medium. Under 70%, the performance is judged satisfactory.

The resulting performance scores are presented as bar charts in Figure 5.3 and Figure 5.4. A colour code is used for performance: green for high, blue for medium and yellow for satisfactory. In terms of presence, performance scores of all subscales for both technologies are higher than 70%, and around half of them reach 80%. It can be concluded that, no matter the hand tracking technology used, the sense of presence induced by the virtual cockpit is more than satisfactory. The global performance score of the Leap Motion on presence is 78.86% and the one of the Hi5 VR Gloves is 80.72%. As for technology capabilities, both systems are also considered as more than satisfactory, with a global performance for the Leap Motion and the VR gloves of 70.54% and 70.01%, respectively. However, in both cases, the interaction and precision performance scores are not more than satisfactory and should be improved. According to the answers of the participants, the ease of interaction is the weak point of the Leap Motion, and precision is the weak point of the Hi5 VR Glove. Additionally, it should be noted that the results of the cybersickness questionnaires revealed that nobody experienced cybersickness.

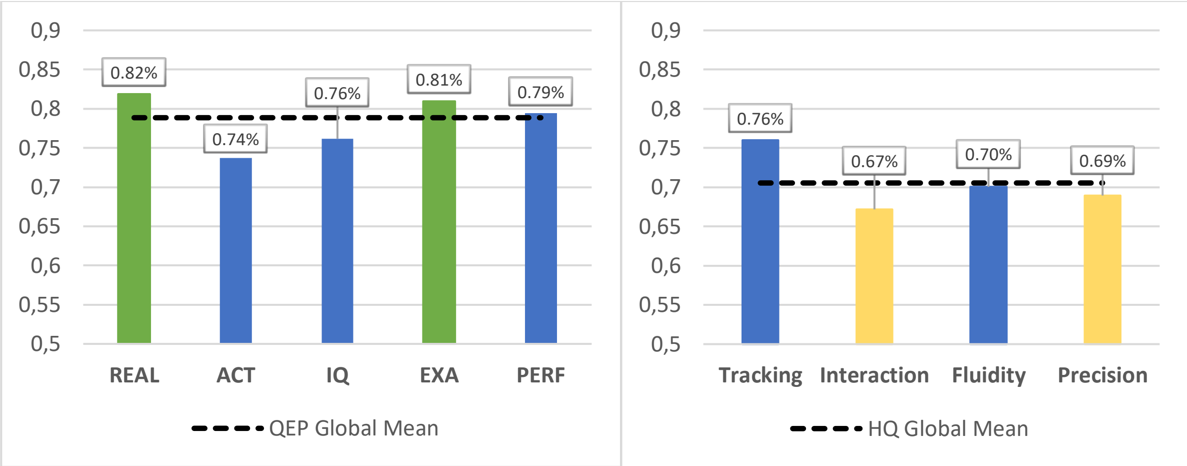


Figure 5.3: Performance scores of the Leap Motion

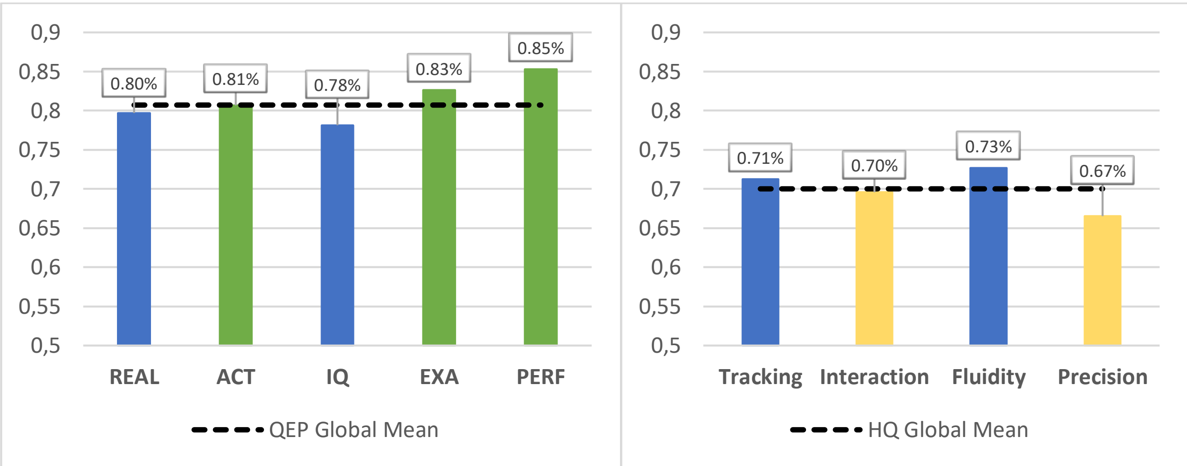


Figure 5.4: Performance scores of the Hi5 VR Gloves

5.3 LIMITATIONS

Several limitations of this comparative study must be acknowledged. First, the small sample size (N = 17) influences the statistical power of the tests carried out. For instance, the subscales “Act” and “Self-assessment of performance” from the QEP might have been significantly influenced by the hand tracking technology if there had been more participants, as suggested by the effect size value. Moreover, two participants had more insight than the others on the goal of the study as they work at the HEC Digital Lab. This also means that they are more familiar with VR than most of the population. Thus, their judgement was probably more critical. The fact that only one size of VR gloves was available for the study is also a limitation because if the participant’s hands were too big or too small, hand and finger tracking was negatively impacted. Finally, the analysis was mostly based on the results of questionnaires. Questionnaires only provide self-reported information and therefore, a lack of objective measures must be admitted.

Chapter 6: Project Management

A project is a "*temporary endeavour undertaken to create a unique product, service or result*" (Project Management Institute, n.d., para. 1). The project analysed in this chapter is the development of a proof of concept (PoC) of an immersive virtual reality flight simulator for pilot training in the preflight procedure. It is consistent with the characteristics of a project as it is a substantial temporary work which has been developed progressively in order to achieve well-defined objectives. The first section of this chapter describes my roles in this project. Section 6.2 presents the first step of the project, the planning stage. Finally, the PoC development phase is dealt with.

6.1 THE ROLES OF PROJECT MANAGER AND PROJECT LEADER

As already explained in section 4.1, ASL Airlines Belgium wants to change its current pilot training system which is unpractical and expensive. For this reason, *ASLB* partnered with the HEC Digital Lab to develop a VR flight simulator. As an intern at the HEC Digital Lab, I took on the role of project manager, but also the role of project leader. The difference between these two roles is that a project leader has a technical profile, monitors the work and leads the team, whereas the project manager has a managerial profile and makes sure that the project is delivered within time, within scope and within budget. For this project, the technical skills required for the role of project leader are mostly programming skills because the interactions with the virtual environment must be programmed. As for the role of project manager, it consists in being the consultant of ASLB at the HEC Digital Lab, reporting the project progress and understanding the requirements and wishes of ASLB, in order to create a PoC which corresponds to their expectations. Therefore, the skills I have developed throughout the Digital Business master's degree allowed me to fulfil the tasks of both roles.

6.2 PLANNING STAGE

In the planning stage, it is first necessary to determine the scope of the project, i.e. what needs to be done to achieve the goals of the project. Thus, the different components of the project must be identified. In the case of the VR flight simulator, four components are essential. The first one is the virtual environment, which must be modelled in 3D. All controls and small elements of a real B737 cockpit must be included because this virtual training environment must be faithful to reality. Moreover, the set of possible interactions with this virtual environment must be implemented. As with any project, good organisation is also important. Finally, the last key component of this project is technical insight in the field of the application, in order to develop a product which is realistic.

After defining what needs to be done, the team that will work on the project must be composed based on the project scope. To model the virtual cockpit and its elements, a computer graphics artist is required. Implementing interactions and other features is the role of a programmer. To ensure good organisation and coordination within the team, a project manager is necessary. Based on these conclusions, the project team was formed, and responsibilities were assigned. It was composed of four people, including myself. Two computer graphics artists worked on the virtual environment. One was assigned to the cockpit itself and the other one to the pilot character. Along with a programmer, I worked on the different aspects of the code. As already said in the previous section, in addition to this technical assignment, I was also the project leader and project manager. It should be noted that for technical insight, technical pilots from *ASLB* will be consulted but they are not directly considered part of the team.

As for time planning, a flexible approach was adopted. Instead of defining a precise schedule as well as deadlines for each of the different activities to be carried out throughout the project, only a final deadline for the overall completion of the PoC was set. Without taking into account the modelling of the cockpit, the team had approximately three months and a half to develop a fully interactive virtual cockpit with a training procedure.

6.3 PROJECT EXECUTION

The technical part of my assignments consisted in programming interactions in C# using Unity 3D as game development platform. Because of the significant workload for such a project in terms of programming, tasks were distributed between the programmers. One of my main responsibilities during the development phase of the PoC was to integrate VR gloves in the virtual environment. I successfully implemented three different gloves and tested them. As a project manager, I was then able to take an informed decision when choosing the VR gloves to be used for the PoC. I also implemented most interactions with the controls for the VR gloves and the Leap Motion, and integrated haptic devices. The other programmer took care of the integration of the motion seat and the pedals, the implementation of the training procedure and a few improvements of interactions.

The biggest challenge when splitting tasks of the same project among programmers is coordination. It was my role as the project leader to ensure that the different parts we worked on could be combined, without repeating the same task twice and losing precious time. The strategy adopted was to assign one main version of the project to one of us and to progressively add components created by the other one to this main version. The compatibility between the new component and the main version was checked directly after combining them in order to identify potential problems as soon as possible. I kept the main version because I had to adjust interactions and define some parameters for all controls. This requires working directly with the Unity Editor and changes made in the Unity Editor cannot easily be added to another version. On the other hand, the tasks assigned to the other programmer mostly required to use scripts, which can easily be transferred from one version to the other. In virtual reality projects, this coordination problem also exists between computer graphics artists and programmers because 3D models and interactions go hand in hand. However, it is less problematic because most of the environment is modelled before working on interactions.

Although the only deadline set during the planning phase was the final deadline, project management does not only consist in planning. During project execution, progressive insight and changes must be taken into account and corrective actions must be initiated if necessary. It should be noted that this is valid for time, scope and resources of the project. It is called monitoring and control. For this reason, new deadlines were progressively added. For instance, a first version of the VR flight simulator had to be presented at the opening ceremony of the HEC Digital Lab, approximately one month after the beginning of the project. Thus, priorities had to be set in order to make sure that essential components would be implemented on time. Furthermore, to consult technical pilots and get their opinion about the under-development PoC, other deadlines were added. Given that pilots are the only persons who can evaluate the realism of the virtual cockpit in terms of visuals and interactions, this was essential. Their feedbacks were used as a basis for scope adjustments.

Chapter 7: Conclusion

Virtual reality was analysed from two different perspectives throughout this thesis. Firstly, a management focus was adopted. Through an extensive literature review of business applications of VR, it has been shown that this technology can be used in various sectors such as retail, healthcare and automotive. The most common applications already implemented by companies are product design, training and remote collaboration. Its main benefits are cost reduction in terms of money and time, increased efficiency, flexibility and the fact that the virtual environment in risk-free.

The first research question aimed to determine if immersive virtual reality was a potential tool for pilot training in the aviation industry. Based on a market research and a competitive analysis of VR desktop flight simulators, it can be deduced that immersive VR has great potential in this sector because competitors, which are mostly X-Plane, Prepar3D and FlyInside, invest in the technology as well. For this reason, ASL Airlines Belgium should differentiate itself by emphasizing the educational and realistic aspects of its future product. Furthermore, based on the results of the comparative study on immersion, the technical feasibility of a VR system for pilot training was confirmed. No matter the hand tracking technology, participants were able to interact with the different controls of the cockpit and to complete the fake preflight procedures. In addition, the global performance scores computed from the questionnaires clearly showed that the proof of concept provides a VR experience which is more than satisfactory in terms of presence, but also in terms of technological capabilities of the hand tracking systems. Moreover, the main negative side effect of VR, cybersickness, was not induced by the virtual cockpit. The proof of concept has also been tested by technical pilots of ASL Airlines Belgium. Although it is only a proof of concept which requires some additional adjustments, these pilots stated that its potential for pilot training was real. Based on all the results presented in this paragraph, it can be concluded that **virtual reality is a potential tool for pilot training in the aviation industry**.

This thesis also included a more technical approach of virtual reality, focusing on immersive technologies and especially hand tracking technologies. The different perspectives on the concepts of immersion and presence, which are essential for an analysis of immersive technologies, were explained in the literature review. Immersion can be considered either as objective or subjective, but the literature agrees that it depends on the technical characteristics of the VR system. As for presence, it is a psychological sense of being in an environment and is positively influenced by the level of immersion. Moreover, different methods to measure presence were presented and previous studies on immersion and presence were briefly summarized. Four different immersive technologies were presented, namely infrared cameras for hand tracking, VR data gloves, haptic devices and a motion seat. Several VR gloves were compared and the final choice of the glove for the proof of concept was the Hi5 VR Glove because of its good price-quality ratio.

The second research question intended to determine which immersive technology was the most suitable for hand tracking in virtual reality. To that end, a comparative study was conducted. Two different immersive technologies for hand tracking were compared, the Leap Motion and the Hi5 VR Gloves. The comparison was essentially based on measures of presence, technology capabilities and performance. None of these measures resulted in a significant difference between the two technologies. Although each of them has this pros and cons, this study concluded that **overall, both hand tracking technologies provide similar virtual reality experiences in terms of presence, interaction, tracking, fluidity and precision**. The comparison of the measures between group A and B revealed that the order in which technologies were tested has a significant impact on the final preference of the participants, but not on the technology capabilities assessment or the level of presence. Nevertheless, the presence scores for the VR gloves only were significantly affected by the order because of an interaction effect between the order and the technology used.

The answer to this second research question also have managerial implications for ASL Airlines Belgium. Indeed, one hand tracking technology must eventually be chosen for the VR flight simulator. Given that both technologies provide similar experiences, my personal suggestion would be to pick the Leap Motion. It is more practical, more hygienic, less fragile and most importantly, it is more than ten times cheaper than the Hi5 VR Gloves combined with HTC Vive trackers. In view of the conclusions of the study, such an investment in the VR gloves is not justifiable. However, it is essential to make interactions with knobs work properly with the Leap Motion in the future. A potential solution could be to click on the knob to display an interface which lets the user choose a value.

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Appendices

Appendix A. Visuals from the VR flight simulator developed for ASLB


CIRCUIT BREAKER
PANEL
EQUIP COOLING
EMER EXIT LIGHTS
BUS TRANS
APU GEN
APU
FUEL PUMPS
RAIN RAPELLENT
WIPER
RUNWAY TURNOFF
TAXI
APU
ENGINE START
LOGO
POSITION STROBE & STEADY
ANTI COLLISION
WING
WHEEL WELL
HEADSET
TEST
ERASE

Appendix B. French adaptation of the Immersive Tendencies Questionnaire of Witmer & Singer (1998)

VOTRE TENDANCE À ÊTRE "IMMERGÉ(E)"

Indiquer votre réponse en inscrivant un "X" dans la case appropriée de l'échelle en 7 points. Veuillez prendre en compte l'échelle en entier lorsque vous inscrivez vos réponses, surtout lorsque des niveaux intermédiaires sont en jeu. Par exemple, si votre réponse est "une fois ou deux", la deuxième case à partir de la gauche devrait être utilisée. Si votre réponse est "plusieurs fois mais pas extrêmement souvent", alors la sixième case (ou la deuxième à partir de la droite) devrait être utilisée.

1. Devenez-vous facilement et profondément absorbé(e) lorsque vous visionnez des films ou des téléfilms ?

☐	☐	☐	☐	☐	☐	☐
Jamais			À l'occasion			Souvent

2. Vous arrive-t-il d'être tellement absorbé(e) dans une émission de télévision ou un livre que les gens autour de vous ont de la difficulté à vous en tirer ?

☐	☐	☐	☐	☐	☐	☐
Jamais			À l'occasion			Souvent

3. Jusqu'à quel point vous sentez-vous mentalement éveillé(e) ou vif(ve) d'esprit en ce moment même ?

☐	☐	☐	☐	☐	☐	☐
Pas éveillé(e)			Modérément			Complètement éveillé(e)

4. Vous arrive-t-il d'être tellement absorbé(e) dans un film que vous n'êtes pas conscient(e) des choses qui se passent autour de vous ?

☐	☐	☐	☐	☐	☐	☐
Jamais			À l'occasion			Souvent

5. À quelle fréquence vous arrive-t-il de vous identifier intimement avec les personnages d'une histoire ?

☐	☐	☐	☐	☐	☐	☐
Jamais			À l'occasion			Souvent

6. Vous arrive-t-il d'être tellement absorbé(e) dans un jeu vidéo que vous avez l'impression d'être à l'intérieur du jeu plutôt qu'en train de manœuvrer des manettes de jeu et de regarder un écran ?

☐	☐	☐	☐	☐	☐	☐
Jamais			À l'occasion			Souvent

7. Comment vous sentez-vous au plan de la forme physique aujourd'hui ?

☐	☐	☐	☐	☐	☐	☐
Pas en forme			Modérément bien			Extrêmement bien

8. Dans quelle mesure êtes-vous efficace pour vous couper des distractions extérieures lorsque vous êtes en train de faire quelque chose ?

- 2 -

☐	☐	☐	☐	☐	☐	☐
Pas très bon(ne)			Plutôt bon(ne)			Très bon(ne)

9. Lorsque vous assistez à un match sportif, vous arrive-t-il de devenir tellement pris(e) par le match que vous réagissez comme si vous étiez un des joueurs ?

☐	☐	☐	☐	☐	☐	☐
Jamais			À l'occasion			Souvent

10. Vous arrive-t-il d'être tellement absorbé(e) dans des rêveries, en plein jour, que vous n'êtes pas conscient(e) des choses qui se passent autour de vous ?

☐	☐	☐	☐	☐	☐	☐
Jamais			À l'occasion			Souvent

11. Vous arrive-t-il d'avoir des rêves qui semblent tellement réels que vous vous sentez désorienté(e) au réveil ?

☐	☐	☐	☐	☐	☐	☐
Jamais			À l'occasion			Souvent

12. Quand vous faites du sport, vous arrive-t-il d'être à ce point absorbé(e) que vous perdez la notion du temps ?

☐	☐	☐	☐	☐	☐	☐
Jamais			À l'occasion			Souvent

13. Dans quelle mesure arrivez-vous à vous concentrer lors d'activités plaisantes ?

☐	☐	☐	☐	☐	☐	☐
Pas du tout			Modérément bien			Très bien

14. À quelle fréquence jouez-vous à des jeux vidéo ? ("Souvent" devrait correspondre à tous les jours, ou tous les deux jours, en moyenne)

☐	☐	☐	☐	☐	☐	☐
Jamais			À l'occasion			Souvent

15. Vous est-il déjà arrivé(e) d'être excité(e) lorsque vous visionnez une scène de poursuite ou de combat à la télévision ou dans un film ?

☐	☐	☐	☐	☐	☐	☐
Jamais			À l'occasion			Souvent

16. Vous est-il déjà arrivé(e) d'être apeuré(e) par quelque chose se produisant à la télévision ou dans un film ?

☐	☐	☐	☐	☐	☐	☐
Jamais			À l'occasion			Souvent

- 3 -

17. Vous est-il déjà arrivé(e) de demeurer apeuré(e) longtemps après le visionnement d'un film d'épouvante ?

☐	☐	☐	☐	☐	☐	☐
Jamais			À l'occasion			Souvent

18. Vous arrive-t-il de devenir absorbé(e) à un point tel dans une activité donnée que vous en perdez la notion du temps ?

☐	☐	☐	☐	☐	☐	☐
Jamais			À l'occasion			Souvent

- 4 -

Appendix C. QEP: French adaptation of the Presence Questionnaire of Witmer et al. (2005)

No dossier ____________________ Date ______________

QUESTIONNAIRE SUR L'ÉTAT DE PRÉSENCE*
Laboratoire de Cyberpsychologie de l'UQO
(2002)

Décrivez votre expérience dans l'environnement en marquant d'un "X" la case appropriée de l'échelle en 7 points, et ce en accord avec le contenu de la question et les étiquettes descriptives. Veuillez prendre en compte l'échelle en entier lorsque vous inscrivez vos réponses, surtout lorsque des niveaux intermédiaires sont en jeu. Répondez aux questions indépendamment les unes des autres et dans l'ordre dans lequel ils apparaissent. **Ne** sautez **pas** de questions et **ne** retournez **pas** à une question précédente afin de modifier votre réponse.

EN FONCTION DE L'ENVIRONNEMENT DANS LEQUEL VOUS ÉTIEZ

1. Dans quelle mesure étiez-vous capable de contrôler les événements?

|________|________|________|________|________|________|________|
PAS DU TOUT ASSEZ COMPLÈTEMENT

2. Dans quelle mesure l'environnement était-il réactif (sensible) aux actions que vous y faisiez?

|________|________|________|________|________|________|________|
PAS RÉACTIF MODÉRÉMENT RÉACTIF COMPLÈTEMENT RÉACTIF

3. Dans quelle mesure vos interactions avec l'environnement vous semblaient-elles naturelles?

|________|________|________|________|________|________|________|
EXTRÊMEMENT ARTIFICIELLES À MI-CHEMIN COMPLÈTEMENT NATURELLES

4. Dans quelle mesure les aspects visuels de l'environnement vous invitaient-ils à vous y impliquer?

|________|________|________|________|________|________|________|
PAS DU TOUT ASSEZ COMPLÈTEMENT

5. Dans quelle mesure les mécanismes permettant votre mouvement dans l'environnement vous semblaient-ils naturels?

|________|________|________|________|________|________|________|

EXTRÊMEMENT ARTIFICIELS — À MI-CHEMIN — COMPLÈTEMENT NATURELS

6. Dans quelle mesure vos sens étaient-ils trompés par le réalisme du mouvement des objets à travers l'espace?

|________|________|________|________|________|________|________|

PAS DU TOUT — MODÉRÉMENT TROMPÉS — TRÈS TROMPÉS

7. Dans quelle mesure les expériences que vous avez vécues dans l'environnement virtuel ressemblaient-elles à celles de l'environnement réel ?

|________|________|________|________|________|________|________|

PAS RESSEMBLANT — MODÉRÉMENT RESSEMBLANT — TRÈS RESSEMBLANT

8. Étiez-vous capable d'anticiper les conséquences des mouvements que vous faisiez?

|________|________|________|________|________|________|________|

PAS DU TOUT — ASSEZ — COMPLÈTEMENT

9. Jusqu'à quel point étiez-vous en mesure d'explorer activement l'environnement de façon visuelle?

|________|________|________|________|________|________|________|

PAS DU TOUT — ASSEZ — COMPLÈTEMENT

10. Jusqu'à quel point la sensation de déplacement à l'intérieur de l'environnement virtuel était-elle confondante (réaliste)?

|________|________|________|________|________|________|________|

PAS CONFONDANTE — MODÉRÉMENT CONFONDANTE — TRÈS CONFONDANTE

17. Jusqu'à quel point la qualité visuelle de l'appareillage graphique vous a-t-elle incommodé(e) dans l'exécution des tâches requises?

|________|________|________|________|________|________|________|

PAS DU TOUT — ASSEZ INCOMMODÉ(E) — TÂCHES COMPLÈTEMENT EMPÊCHÉES

18. Dans quelle mesure les mécanismes de contrôle de votre mouvement ont-ils interféré avec l'exécution des tâches requises?

|________|________|________|________|________|________|________|

PAS DU TOUT — ASSEZ INTERFÉRÉ — GRANDEMENT INTERFÉRÉ

19. Jusqu'à quel point êtes-vous parvenu(e) à vous concentrer sur les tâches requises plutôt que sur les mécanismes utilisés pour effectuer lesdites tâches?

|________|________|________|________|________|________|________|

PAS DU TOUT — ASSEZ — COMPLÈTEMENT

RÉPONDEZ SI L'ENVIRONNEMENT VIRTUEL COMPRENAIT DES SONS :

20. Dans quelle mesure les aspects auditifs de l'environnement vous invitaient-ils à vous y impliquer?

|________|________|________|________|________|________|________|

PAS DU TOUT — ASSEZ — COMPLÈTEMENT

21. Dans quelle mesure arriviez-vous à identifier correctement les sons produits dans l'environnement?

|________|________|________|________|________|________|________|

PAS DU TOUT — ASSEZ — COMPLÈTEMENT

22. Dans quelle mesure arriviez-vous à localiser correctement les sons produits dans l'environnement?

|________|________|________|________|________|________|________|

PAS DU TOUT — ASSEZ — COMPLÈTEMENT

11. À quelle distance pouviez-vous examiner les objets?

|________|________|________|________|________|________|________|

PAS PROCHE DU TOUT	PLUTÔT PROCHE	TRÈS PROCHE

12. Jusqu'à quel point pouviez-vous examiner les objets sous différents angles?

|________|________|________|________|________|________|________|

PAS DU TOUT	ASSEZ	COMPLÈTEMENT

13. Jusqu'à quel point étiez-vous impliqué(e) dans l'expérience vécue dans l'environnement virtuel?

|________|________|________|________|________|________|________|

PAS DU TOUT ENGAGÉ(E)	MOYENNEMENT ENGAGÉ(E)	COMPLÈTEMENT ABSORBÉ(E)

14. Jusqu'à quel point avez-vous ressenti un délai séparant vos actions de leurs conséquences?

|________|________|________|________|________|________|________|

AUCUN DÉLAI	DÉLAI MODÉRÉ	LONG DÉLAI

15. À quel rythme vous êtes-vous adapté(e) à l'expérience vécue dans l'environnement virtuel?

|________|________|________|________|________|________|________|

PAS ADAPTÉ(E) DU TOUT	LENTEMENT	EN MOINS D'UNE MINUTE

16. En termes d'interactions et de déplacements dans l'environnement virtuel, jusqu'à quel point vous sentiez-vous compétent(e) à la fin de l'expérience?

|________|________|________|________|________|________|________|

PAS COMPÉTENT(E)	RAISONNABLEMENT COMPÉTENT(E)	TRÈS COMPÉTENT(E)

Appendix D. Hand questionnaire for technological capabilities (HQ)

Questions spécifiques à la représentation des mains

Veuillez répondre aux questions suivantes en plaçant une croix sur la ligne à l'endroit qui correspond le mieux à votre ressenti. La ligne représente une échelle continue entre 1 et 10.

☐ A quel point aviez-vous l'impression que vos mains virtuelles se situaient au même endroit que vos mains physiques ?

0 10

☐ Avez-vous facilement interagi avec les boutons ?

0 10

☐ Comment évalueriez-vous la fluidité des mouvements ?

0 10

☐ Comment évalueriez-vous la précision des mouvements ?

0 10

Appendix E. Cybersickness questionnaire

Questionnaire sur les cybermalaises*
Laboratoire de Cyberpsychologie de l'UQO
(Traduit de Kennedy, R.S.et al., 1993)

Numéro____________________________ Date____________________

Consignes : Encerclez à quel point chaque symptôme ci-dessous vous affecte présentement.

1. Inconfort général	Pas du tout	Un peu	Modérément	Sévèrement
2. Fatigue	Pas du tout	Un peu	Modérément	Sévèrement
3. Mal de tête	Pas du tout	Un peu	Modérément	Sévèrement
4. Fatigue des yeux	Pas du tout	Un peu	Modérément	Sévèrement
5. Difficulté à faire le focus	Pas du tout	Un peu	Modérément	Sévèrement
6. Augmentation de la salivation	Pas du tout	Un peu	Modérément	Sévèrement
7. Transpiration	Pas du tout	Un peu	Modérément	Sévèrement
8. Nausées	Pas du tout	Un peu	Modérément	Sévèrement
9. Difficulté à se concentrer	Pas du tout	Un peu	Modérément	Sévèrement
10. Impression de lourdeur dans la tête	Pas du tout	Un peu	Modérément	Sévèrement
11. Vision embrouillée	Pas du tout	Un peu	Modérément	Sévèrement
12. Étourdissement les yeux ouverts	Pas du tout	Un peu	Modérément	Sévèrement
13. Étourdissement les yeux fermés	Pas du tout	Un peu	Modérément	Sévèrement
14. *Vertiges	Pas du tout	Un peu	Modérément	Sévèrement
15. **Conscience de l'estomac	Pas du tout	Un peu	Modérément	Sévèrement
16. Rots	Pas du tout	Un peu	Modérément	Sévèrement

* Les vertiges sont vécus comme une perte de l'orientation par rapport à la position verticale.
** L'expression « conscience de l'estomac » est habituellement utilisée pour désigner un sentiment d'inconfort sans nausée.

Dernière version : Mars 2013

***Version originale : Kennedy, R.S., Lane, N.E., Berbaum, K.S., & Lilienthal, M.G. (1993). Simulator Sickness Questionnaire: An enhanced method for quantifying simulator sickness. *International Journal of Aviation Psychology, 3*(3), 203-220

Appendix F. Raw data from the QEP questionnaire for both LM and G

Participant	**Group**	*REAL_LM*	*ACT_LM*	*IQ_LM*	*EXA_LM*	*PERF_LM*	**QEP LM**
1	A	40	21	12	19	12	104
2	A	42	21	17	18	13	111
3	A	38	23	15	16	10	102
4	A	35	14	14	15	9	87
5	A	47	25	20	20	12	124
6	A	38	20	15	17	9	99
7	A	37	25	19	18	11	110
8	A	41	16	15	17	7	96
9	A	41	23	16	18	10	108
10	B	34	16	13	16	13	92
11	B	49	26	18	17	14	124
12	B	39	24	15	17	11	106
13	B	47	23	20	21	12	123
14	B	36	14	13	12	11	86
15	B	46	18	18	15	11	108
16	B	43	24	15	17	13	112
17	B	29	18	17	16	11	91

Participant	**Group**	*REAL_G*	*ACT_G*	*IQ_G*	*EXA_G*	*PERF_G*	**QEP G**
1	A	47	27	12	19	13	118
2	A	48	28	21	20	14	131
3	A	39	23	15	19	12	108
4	A	33	23	15	15	12	98
5	A	46	27	21	21	14	129
6	A	40	25	20	17	13	115
7	A	37	22	20	18	12	109
8	A	45	24	19	20	13	121
9	A	41	26	16	16	11	110
10	B	40	22	18	16	12	108
11	B	36	18	11	20	12	97
12	B	37	20	14	17	10	98
13	B	44	24	21	20	12	121
14	B	40	18	11	12	9	90
15	B	39	22	18	15	11	105
16	B	26	18	13	15	11	83
17	B	26	17	14	15	12	84

Appendix G. Raw data from HQ for both LM and G

Participant	Group	HQ1_LM	HQ2_LM	HQ3_LM	HQ4_LM	HQ LM
1	A	8	6,7	5,9	8	28,6
2	A	7,5	8	7,6	7,5	30,6
3	A	5,7	7,5	7,3	5,3	25,8
4	A	2,5	2,5	2,5	2,5	10
5	A	9	9	9	8	35
6	A	8,4	7,7	8,3	7,5	31,9
7	A	6	6	6,3	7,2	25,5
8	A	7,4	2,4	6,5	6,6	22,9
9	A	8,5	9	8,9	8	34,4
10	B	7,5	7	7	7,8	29,3
11	B	8,5	8	7	9	32,5
12	B	8,2	7,3	7,3	6,7	29,5
13	B	9,2	6,3	7,6	5	28,1
14	B	6	5,9	5,1	7	24
15	B	10	7	7	7	31
16	B	9,4	8,5	9,3	7,7	34,9
17	B	7,4	5,4	6,5	6,4	25,7

Participant	Group	HQ1_G	HQ2_G	HQ3_G	HQ4_G	HQ G
1	A	9,5	9,5	9,5	9,5	38
2	A	9	8,6	8,6	8,6	34,8
3	A	3,3	7,6	5,6	5,5	22
4	A	5,5	6,3	5,5	5,5	22,8
5	A	8	9	10	10	37
6	A	6,7	8,9	8,3	7,4	31,3
7	A	5,2	5,7	6,3	5,3	22,5
8	A	9,4	7,4	9,4	7,4	33,6
9	A	10	8,4	9,5	10	37,9
10	B	7,4	7	7	7,8	29,2
11	B	6,4	5,5	7,5	6,6	26
12	B	6,4	6,3	5,3	5,3	23,3
13	B	9,8	7,4	6,2	8,3	31,7
14	B	9	6	8	6	29
15	B	6,1	7,4	6,9	6,5	26,9
16	B	7	3	4,6	1	15,6
17	B	2,4	4,3	5,4	2,4	14,5

Appendix H. TTC measurements for LM and G (in seconds) and preferences

Participant	Group	TTC_LM	TTC_G	Preference
1	A	374	199	G
2	A	510	244	G
3	A	454	323	LM
4	A	318	250	G
5	A	290	200	G
6	A	680	328	G
7	A	335	252	LM
8	A	404	182	LM
9	A	403	217	G
10	B	267	207	LM
11	B	256	578	LM
12	B	265	286	LM
13	B	160	197	LM
14	B	455	465	G
15	B	275	283	LM
16	B	381	566	LM
17	B	260	299	LM

Appendix I. Descriptive statistics of QEP subscales and HQ items for each immersive technology

	Subscale	Mean	SD	SE
QEP	REAL_LM	40.12	5.278	1.280
	REAL_G	39.06	6.388	1.549
	AGIR_LM	20.65	3.968	0.962
	AGIR_G	22.59	3.465	0.840
	QI_LM	16.00	2.424	0.588
	QI_G	16.41	3.589	0.871
	EXA_LM	17.00	2.062	0.500
	EXA_G	17.35	2.523	0.612
	PERF_LM	11.12	1.764	0.428
	PERF_G	11.94	1.298	0.315
HQ	HQ1_LM	7.600	1.788	0.434
	HQ1_G	7.124	2.232	0.541
	HQ2_LM	6.718	1.912	0.464
	HQ2_G	6.959	1.739	0.422
	HQ3_LM	7.006	1.611	0.391
	HQ3_G	7.271	1.733	0.420
	HQ4_LM	6.894	1.505	0.365
	HQ4_G	6.653	2.453	0.595

Appendix J. Marginal means for QEP and HQ

Dependent variable	Group	Technology used	Mean	SE
QEP	A	LM	104.56	4.17
		G	115.44	3.90
	B	LM	105.25	4.42
		G	98.25	4.14
HQ	A	LM	27.19	2.03
		G	31.10	2.21
	B	LM	29.37	2.15
		G	24.52	2.34

Executive Summary

Around five years ago, virtual reality (VR) came back in the spotlight after years of oblivion among the general public. During those years, tremendous technological advances in the field occurred, leading to a resurgence of the technology. Even if it is common to associate virtual reality with the entertainment industry, the corporate world considers it as a key technology for more efficient operations. Moreover, various immersive technologies are developed to enhance virtual reality experiences. Therefore, two different aspects of immersive virtual reality are covered within the scope of this master thesis: virtual reality at the service of companies and hand tracking technologies.

After defining essential concepts of virtual reality, a literature review of business applications is conducted to describe the overall potential of the technology. This managerial approach is also adopted to answer the first research question, seeking to determine if the aviation industry could make use of immersive virtual reality for pilot training. A case study on ASL Airlines Belgium (ASLB) is used as a basis to provide an answer. After analysing the market of virtual reality flight simulators and developing an immersive proof of concept, the technical feasibility of the virtual reality system is confirmed and a differentiation strategy is suggested, based on a competitive analysis.

The second research question is more technical and deals with the comparison between two hand tracking immersive technologies in virtual reality, namely the Leap Motion and the Hi5 VR Gloves. Before analysing these immersive technologies, immersion and presence concepts are presented. Then, a comparative study between the two technologies is conducted using a within-subject experimental design. The proof of concept developed for ASLB serves as virtual environment for the experiments. Results show that the Leap Motion and the Hi5 VR Gloves provide a similar virtual reality experience in terms of presence, tracking, interaction, fluidity and precision. The findings contribute to research on immersive technologies but can also be useful to draw managerial conclusions for ASLB. Indeed, given the findings and the large price difference between the two hand tracking technologies, the cheapest one should be selected for the proof of concept, that is to say the Leap Motion.