UNIVERSIDAD DE BURGOS

Programa de Doctorado *«Humanidades y Comunicación»*

Advantages and Limitations of Immersive Virtual Reality Educational Applications in Learning

PhD Thesis

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ABSTRACT

Although virtual reality technologies have been with us since the late 1950s, their very limited use in educational contexts is mainly due to the high cost of the equipment and the lack of suitable educational content. Today, the wide availability on the market of affordable software and hardware tools designed for immersive Virtual Reality (iVR) experiences might suggest a very promising future to enhance learning. However, there is still a long way to go to determine how iVR can be used and to what extent it can reach its potential as an educational tool. Three published papers are presented in this PhD Thesis that report the results of research into iVR technology and its use as a learning tool at undergraduate level.

The first study presents a critical review of the literature on iVR for learning purposes. Firstly, it provides a deeper understanding of the use and the benefits of iVR technologies as learning tools. Secondly, it evaluates the possibilities and the limitations of state-of-the-art iVR learning experiences. Finally, it identifies the barriers to their incorporation in educational programs.

The second study describes the design and testing of an iVR experience to evaluate the possibilities and limitations of Immersive Virtual Reality Environments (iVRE) for didactic purposes, especially in topics related to cultural heritage. The suitability of iVR for teaching was evaluated through a questionnaire on historical knowledge and urban layout administered to a large sample of students (n=100). In this study, two teaching methodologies are compared: on the one hand, an iVR experience and, on the other hand, the viewing of a video. The responses of the students underlined the effectiveness of both methodologies: the video group achieved higher scores for historical knowledge and the iVR experience was the most effective method to transmit the knowledge learned through interaction and viewing. Finally, spatial localization was clearly a better acquired skill following the iVR experience.

The third study describes the design of an educational experience and its testing, to evaluate the possibilities and limitations of iVR in concepts associated with computer hardware assembly. The iVR experience is compared with two other learning methodologies adapted to online learning among a large sample of students (n=77): 1) a conventional online class; and 2) the same experience played on a desktop PC. The results showed the strong potential of iVR experiences to improve student well-being at times of isolation, due to higher learning satisfaction levels. In addition, ease of use and the use of in-game tutorials are directly related to game user satisfaction and performance. Although a very limited effect on learning theoretical knowledge was observed with the application of iVR compared to the other methodologies, this effect was significantly improved by visual knowledge, understanding and by making connections between different concepts.

These experiences demonstrate that: 1) iVR improves student satisfaction with the learning process; 2) provides significant advantages compared to other methodologies for the absorption of visual knowledge; 3) slightly improves acquisition of theoretical knowledge; and 4) is especially suitable for the development of an understanding of the different concepts and their connections.

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AUTHOR’S DECLARATION

La tesis «Advantages and limitations of Immersive Virtual Reality educational applications in learning», que presenta D. David Checa Cruz para optar al título de doctor, ha sido realizada dentro del programa «Humanidades y Comunicación», de la Universidad de Burgos, bajo la dirección del doctor D. Andrés Bustillo Iglesias. El director autoriza la presentación del presente documento como memoria para optar al grado de Doctor por la Universidad de Burgos y que cumple con los requisitos para poder optar a la Mención Internacional.

V.B. del director:

Dr. Andrés Bustillo Iglesias

TABLE OF CONTENTS

List of Tables

List of Figures

1. PhD dissertation

1. Introduction

This introductory chapter presents ideas, concepts and research topics that have been addressed throughout the development of this thesis. Immersive Virtual Reality (iVR) is the main and transversal theme of all the research carried out; undoubtedly a relevant and interesting topic nowadays. Although iVR can be used in a wide variety of applications, this thesis is focused on its use in educational applications. This introduction is structured into five sections. Section 1.1 introduces the main concepts of iVR, showcasing the different VR technologies and key features and types of iVR experiences. Section 1.2 details the learning theories and how they apply to iVR. Section 1.3 explains the process of designing iVR educational experiences. Finally, Sections 1.4 and 1.5, respectively, present the advantages and limitations of iVR for learning.

1.1 Immersive Virtual Reality main concepts

The concept of Virtual Reality (VR) can be traced back to the 1960s, with the appearance of the first Head-Mounted Displays (HMD), at which time Ivan Sutherland, described VR as "a window through which a user perceives the virtual world as if [it] looked, felt, sounded real and in which the user could act realistically" (Sutherland, 1965). Later on, VR was defined as "the sum of the hardware and software systems that seek to perfect an all-inclusive, sensory illusion of being present in another environment" (Biocca & Delaney, 1995). More recently, Blascovich (Blascovich, 2002) stated that a virtual environment becomes an immersive virtual environment when it "creates a psychological state in which the individual perceives himself or herself as existing within the virtual environment". Finally, a more technically precise definition might define VR as a computer-generated graphical simulation of the world that allows the user to interact in real time with the artificial world (Burdea & Coiffet, 2003). These definitions present a concept for VR as a particular type of experience rather than just a technology. It will, therefore, be convenient to approach the analysis of VR from different perspectives: firstly, from the perspective of the technology that is used, secondly according to the key features underlying VR, and thirdly considering the different experiences that this technology can provide.

1.1.1. VR technologies

From a technological point of view, VR can be described as the combination of different technologies that integrate various media in a 3D environment, providing interaction through the use of multiple input/output devices. The users know that the environment they perceive is the output of a specific piece of equipment, and it does not exist in the physical world. VR technology can be classified according to the characteristics of the equipment and tools with regard to the levels of interaction and immersion that it can enable. The following classification of VR devices, is generally accepted:

Non-immersive systems: those in which the virtual world is presented in a simple way, such as a computer screen. This technology provides a computer-generated environment to interact with, but keeps the user in contact with the physical environment. *Desktop VR* solutions offer these sorts of systems.

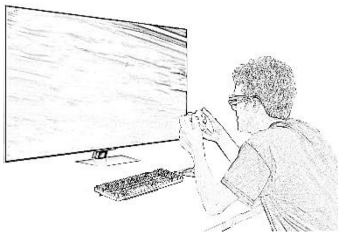

FIGURE 1: USER INTERACTING WITH A NON-IMMERSIVE SYSTEM.

In these solutions, the application is displayed usually through a monitor (that can be 3D) and interaction with the virtual environment is performed using a keyboard, mouse or joystick (Lee & Wong, 2014). There are also more elaborate systems with specialized integrated VR controllers, which offer different degrees of freedom and different possibilities for haptic interaction (Ritterfeld et al., 2009). An example of a non-immersive VR experience is a video game as shown in Figure 1.

Immersive systems: those in which the user feels completely enveloped by the virtual world that is simulated. According to their operating characteristics, different types of immersive systems can be used for different applications.

- *Cave Automatic Virtual Environments (CAVE systems):* A CAVE system is a room in which all the walls, as well as the floor, are projection screens. Typically using 3D glasses and external tracking elements, users will interact and move with the illusion of being in the virtual environment (Freina & Ott, 2015). The advantages of these systems are easy collaboration, as the operator can interact at the same time in both the virtual and the real world. They give users the perception of being in a different reality as long as they are focused on the digital image, but they also keep users in connection with their physical surroundings.

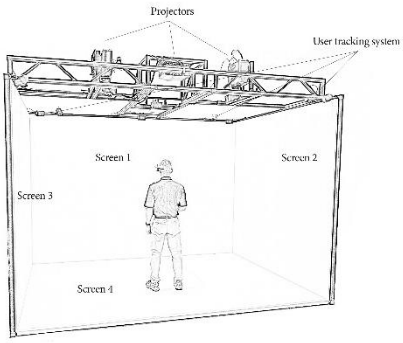

FIGURE 2: USER INSIDE A CAVE AUTOMATIC VIRTUAL ENVIRONMENT.

- *Head Mounted Displays (HMDs) connected to a computer*: These headsets are tethered to powerful computers. These workstations can be used to simulate complex, interactable and realistic environments. The need for this connection to powerful computers makes them less common in educational environments. These devices are normally equipped with built-in tracking systems that monitor six Degrees of Freedom (6DoF). 6DoF devices can track the translational movement of the user, processing whether the HMD has moved in any direction.

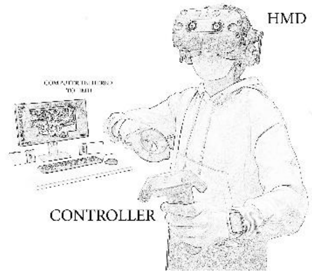

FIGURE 3: USER WITH AN HMD TETHERED TO A COMPUTER.

- *Standalone HMDs*: These are untethered headsets and therefore capable of autonomous operation. They allow more freedom of movements as no wire is required, but are limited in terms of graphic power and autonomy. A distinction is made between low-end and high-end devices.
    - Low-end standalone HMDs: devices that work with either smartphones (*e.g.,* Google Cardboard) or as standalones (*e.g.,* Oculus Go). These devices permit three degrees of freedom (3DoF; roll, pitch, yaw), which makes them ideal for applications using 360º videos.
    - High-end standalone HMDs: devices that are normally equipped with built-in 6DoF tracking. Although their limited processing power restricts their ability to recreate complex and ultra-realistic environments, 6DoF capabilities provide a more extended field of learning methodologies.

FIGURE 4: USER WITH A STANDALONE HMD.

VR experiences accessed through an HMD are generally regarded as high immersion, because the user is completely surrounded within a VR environment (Makransky & Lilleholt, 2018). Simulations or 3D worlds accessed through a desktop computer or tablet are known as low-immersion VR. The emerging availability of low-cost, high-fidelity VR environments has opened up new possibilities for direct learning. Besides, they are both cost effective and scalable, relegating less immersive and much more expensive systems such as CAVEs to the background. Therefore, in this thesis we focus on the use of high-end HMDs. Thus, from now on, the term Immersive Virtual Reality (iVR) will be used. Unlike a lot of research that uses the term Virtual Reality (VR) to refer to non-immersive devices, iVR does not include the less immersive systems.

1.1.2. Key features of iVR

Presence, immersion, engagement and interactivity have been identified as the key features of iVR technologies (Mütterlein, 2018).

Presence is, within the context of Virtual Reality, defined as the illusion of 'being there', understood as the result of the interaction between the user and the computer-generated graphical simulation of the environment to the point that the virtuality of the environment goes unnoticed and is made to feel like the dominant reality (Barfield, W., Zeltzer, D., Sheridan, T.B., Slater, 1995). Whether or not the illusion of presence is achieved, the user tends to behave as if in a real-life situation, despite being aware of a computer-simulated environment (Ai-Lim Lee et al., 2010).

Immersion has repeatedly been associated with presence (Makransky & Petersen, 2019), yet both terms should not be confused. Immersion refers to the quality and ability of a system to present a vivid environment while shutting out the physical reality (Slater, 2003). In contrast, presence, as defined above, is the subjective psychological response of a user to the VR system experience. Some authors stated that the more immersive the system, the more likely the individual will feel present and the more likely the virtual environment will dominate over the physical reality (Cummings & Bailenson, 2016). Presence therefore relates to the psychological feeling of being present in the virtual environment and immersion relates to the properties of the systems that facilitate the feeling of presence (Slater & Wilbur, 1997).

Engagement (also sometimes referred as involvement) refers to the attention that the user devotes to the virtual environment (Gutierrez-Maldonado et al., 2010). Low engagement denotes a lack of user motivation to act or to react to events in the virtual environment. This feature is closely related to the previous ones, because heightening both immersion and presence increases user engagement (Jennett et al., 2008).

Interactivity is a technical feature related to the user sense of control (Sawyer et al., 2017). It refers to the extent to which the user can influence and modify the virtual environment (Steuer, 1992). The amount of interaction depends on: 1) the speed of interaction (response time of the medium in terms of latency regarding user interactions); 2) the number of attributes that can be manipulated in the VE and the quantity of possible interactions and the connection between human actions; and 3) the resulting actions within the environment (Steuer, 1992). According to the user's skills at interacting with the virtual environment, different types of iVR experiences are identified, as discussed in the following section.

1.1.3. Type of experiences

Immersive virtual reality experiences can be categorized into four classes according to the technical characteristic of interactivity:

- *Explorative interaction experiences* are those experiences that allow the user to explore and to interact freely with the virtual environment. They allow users to move freely through space and interact with most of the objects involved in the simulation.
- *Explorative experiences* are more restricted solutions, which allow free exploration of the virtual environment, although no direct interaction. It is possible for the operator to navigate freely but the user has almost no direct interaction capabilities with the objects present in the simulation.
- *Interactive experiences* permit user interaction with the environment, but no free movement through it. Generally, users can interact with any nearby objects. However, they do not have the ability to move around the virtual environment, beyond a very limited surrounding area.
- *Passive experiences* are the most restricted solution in which user interactivity and movement are very limited. The use of passive experiences is clearly related to the use of 3DoF devices, due to their technical limitations affecting movement and interaction.

Creating explorative interaction experiences is complex and costly. Besides, no clear use of this type of experiences for learning is evident, because the user has no clear objective in the VR-environment. Their use is therefore mainly restricted to complementary features and they are not a main learning resource in the educational process. Besides they are nowadays too expensive for mass use, but they show promising potential for future growth. Explorative experiences can be particularly suitable for experiences that require no direct interaction with the environments. For example, in experiences that recreate or reconstruct historical or significant locations users can freely explore the environment at their own pace. Interactive experiences appear to be the most balanced approach, due to the equilibrium between cost, technological development, immersive capabilities and engagement enhancement potential. They are more affordable than exploratory interaction experiences that require full development of the iVR environment. The iVR environment will only have to be developed in high detail in areas where users can see or reach from their position, while any secondary area can be roughly modelled, saving costly human and computational resources in its development. Finally, passive experiences are usually associated with devices without direct interaction capabilities or with low computational resources. Despite being the most restrictive, they are interesting due to their low economic development costs.

1.2 Learning theories and iVR

After introducing the psychological and technological perspective on iVR, this section aims to connect this technological knowledge with established pedagogical theories. Education is often slow to adopt technological improvements (Selwyn, 2011). In the last decade, the democratization of iVR technologies has allowed their growing use in educational contexts. While iVR is costly and not necessarily effective, what does it bring to the table compared to traditional education? iVR is thus one step ahead in the incorporation of technology in the classroom (as was previously the case with videos, computers...). However, it is common to find iVR applications with an absence of learning theories, designed without taking into account either the rationality of the design or the user experience (Fowler, 2015). A prerequisite for an effective iVR educational application is its pedagogical approach and the learning theory it applies (Mikropoulos & Natsis, 2011). Learning theories can be categorized according to how learners assimilate, process and retain the information they have learned (Pritchard, 2017).

The *constructivist* learning paradigm is an essential element in the use of iVR as a pedagogical tool. According to the constructivist approach, the student should actively participate in the process by interacting with the environment (Fosnot & Perry, 1996). According to this theory (Duffy & Jonassen, 2013; Fosnot & Perry, 1996) learning is an active process, whereby learners construct knowledge for themselves (as opposed to passively receiving information). The constructivist philosophy holds that learning is obtained when the student takes an active role, constructing knowledge in a learning-by-doing situation. Thus, by interacting with the learning process, scholars not only acquire information but also connect it to previous knowledge, allowing the creation of new knowledge (Huang & Liaw, 2018). iVR offers a controlled environment in which learners can navigate and manipulate virtual objects, so that they can explore the reactions and effects of those manipulations in real time and construct their own knowledge through a first-person learning-by-doing experience. iVR is a technology that offers similar levels of interaction/manipulation with the environment in much the same way as real experiences (Jen Chen, 2009). These iVR capabilities are entirely compatible with the core axioms of constructivist learning (Winn, 1993).

Constructivism emphasizes that learning is an active, constructive process. Learners actively construct their subjective representations and understandings of reality. New information is linked to each learner's prior knowledge and, therefore, mental representations are subjective (Fosnot & Perry, 1996). Therefore, this theory argues that experience has to provide support for learners to construct their knowledge and to engage them in learning. This support includes tools such as related cases, information resources, collaboration and contextual support as well as redundancy principles to reinforce the learning process. It is appropriate for learning tasks that demand high levels of processing, so that iVR fits seamlessly into the constructivist learning design (Sharma et al., 2013).

In *behaviorism*, appropriate instructional stimuli lead to desired learning outcomes, emphasizing practice and performance (Skinner, 1989). The application of its key aspects to iVR seeks to stimulate student participation through the presentation of the correct stimuli. In this way, learners can learn by doing through trial and error, and iVR presents a safe and engaging space for this process to take place.

Cognitivism is focused on understanding mental processes. Learning results from participation in an environment that fosters both the discovery and the assimilation of knowledge (Shuell, 1986). Cognitive strategies such as schematic organization will fit learning tasks requiring an increased level of processing and iVR-based learning can strengthen cognitivist learning design (Dede, 2009).

Connectivism suggests that people do not stop their learning after completing formal education. By making use of new technological tools they continue learning and acquiring knowledge outside the traditional channels of education (Michelle, 2011). iVR experiences can enable internal and external knowledge networks to facilitate new knowledge building or constructing new meanings that add to existing knowledge.

iVR learning experiences have the potential to achieve learning objectives across cognitive processes and knowledge dimensions. Most VR learning experiences in the literature combine two or more instructional strategies, depending on the goals of the learning experiences and the extent or complexity of the experience design. These main learning paradigms provide a pedagogical framework and a basis for designing an intervention. Of course, there are also many varieties of learning theories developed for direct or indirect use of iVR experiences. Table 1 shows the most common ones used in learning research.

Summarizing, it could be argued that the promotion of iVR-based learning is linked to a fusion of principles from multiple pedagogical perspectives. Regardless of which learning theories under each paradigm are used, it is crucial for the development of iVR applications to be firmly grounded in existing learning theories, because these theories offer guidelines on the motivations, learning process and learning outcomes of the learners.

TABLE 1: MOST WIDELY USED LEARNING THEORIES IN LEARNING RESEARCH.

COGNITIVE THEORY OF MULTIMEDIA LEARNING (CTML): Adding iVR to a lesson might create extraneous processing, exceeding the student's ability to engage in cognitive processes that can make sense of the material. Extraneous processing might accentuate the challenge of selecting, organizing, and integrating relevant information for the student (Mayer, 2005).

COGNITIVE LOAD THEORY (CLT): The amount of sensory information the student receives while interacting with the iVR experience could increase extraneous cognitive load that might have a negative effect on task completion and learning (Sweller et al., 1998, 2019).

GENERATIVE LEARNING THEORY (GLT): Stimulate learners to reflect on prior knowledge and to integrate it with the learning material. iVR help the learner to construct a more meaningful mental representation of the material (Osborne & Wittrock, 1985):

JEFFRIES SIMULATION THEORY: Students learn through experiences in a trusted environment that is incorporated in the iVR design (Jeffries et al., 2015).

SITUATED LEARNING: Employs a constructivist approach in that students learn professional skills by actively participating in the iVR experience (Huang et al., 2010).

EMBODIED COGNITION FRAMEWORK: This theory implies that there is a connection between our motor and visual senses. Therefore, the more explicit the connection, as within iVR experiences, the easier learning becomes (Wilson, 2002):

OPERATIONAL LEARNING: The contexts, activities and social interactions in the iVR learning environment promote the construction of new knowledge (Zhou et al., 2018).

CONTROL VALUE THEORY OF ACHIEVEMENT EMOTIONS (CVTA): The sensations of enjoyment and engagement that iVR produces will benefit performance, because the learner focuses attention on the task, which leads to higher intrinsic and extrinsic student motivation (Pekrun & Stephens, 2010).

INTEREST THEORY: Students work harder when they are intrinsically interested in the material (Schiefele et al., 1992).

INQUIRY-BASED LEARNING (IBL): Students learn by independently conducting their own research (Mieg, 2019).

COGNITIVE AFFECTIVE THEORY OF LEARNING WITH MEDIA (CATLM): Cognitive processes are influenced by affective states, for example by motivation (Moreno Roxana and Mayer, 2007).

COGNITIVE AFFECTIVE MODEL OF IMMERSIVE LEARNING (CAMIL): Describes six affective and cognitive factors that can lead to iVR-based learning outcomes: interest, motivation, self-efficacy, embodiment, cognitive load, and self-regulation (Makransky & Petersen, 2021).

DALE'S CONE THEORY: Students learn best when they go through a real experience or the experience is realistically simulated as within iVR experiences (Dale, 1946).

GAME-BASED LEARNING: Students learn through a gamification process (Bryan et al., 2018).

CONTEXTUAL LEARNING: Students learn by emphasizing the context (Chen, 2016).

1.3 Design procedure of iVR educational experiences

The use of Virtual Reality by itself does not automatically improve learning, even when learners report very high satisfaction rates (Makransky, Terkildsen, et al., 2019). Most research gives no consideration to nor explains how the Immersive Virtual Reality Learning Environments (iVRLEs) are designed and used to enhance learning. Although there is considerable research in which off-the-shelf games are used and, therefore, it has to adapt to what they already offer. As a result, it is more convenient to develop your own iVR applications to improve learning. However, in many cases these applications do not take learning theories into account and researchers do not explain how the game is developed, to achieve its objective of improving learning. Nowadays, developing an iVR application is expensive (in terms of time and money) and needs a multidisciplinary team. In this section, some of the key features needed for the design and successful use of an iVRLE in education are presented. Three stages are followed for the development of an educational application in iVR: pre-design, design and evaluation. Figure 5 summarizes the flow chart for the design and implementation of an iVRLE.

In the first stage, the *pre-design*, a breakdown of the requirements included the definition of the target audience and the application domain. The learning objective must be important and enhanced by the introduction of immersive VR technologies. For example, it can focus on difficult-to-understand problems or learning that has proven to be resistant to conventional pedagogy. In this initial phase, the iVR experience was defined by taking into account the four key objectives for an iVRLE: interaction, immersion, user involvement and, to a lesser extent, photorealism (Roussos et al., 1999). Depending on the target audience and the scope of application, each objective will play a different role. Finally, the educational objectives must also be defined. Learning goals must be well-established, so that the user will not become lost in the amusement of the iVRLE.

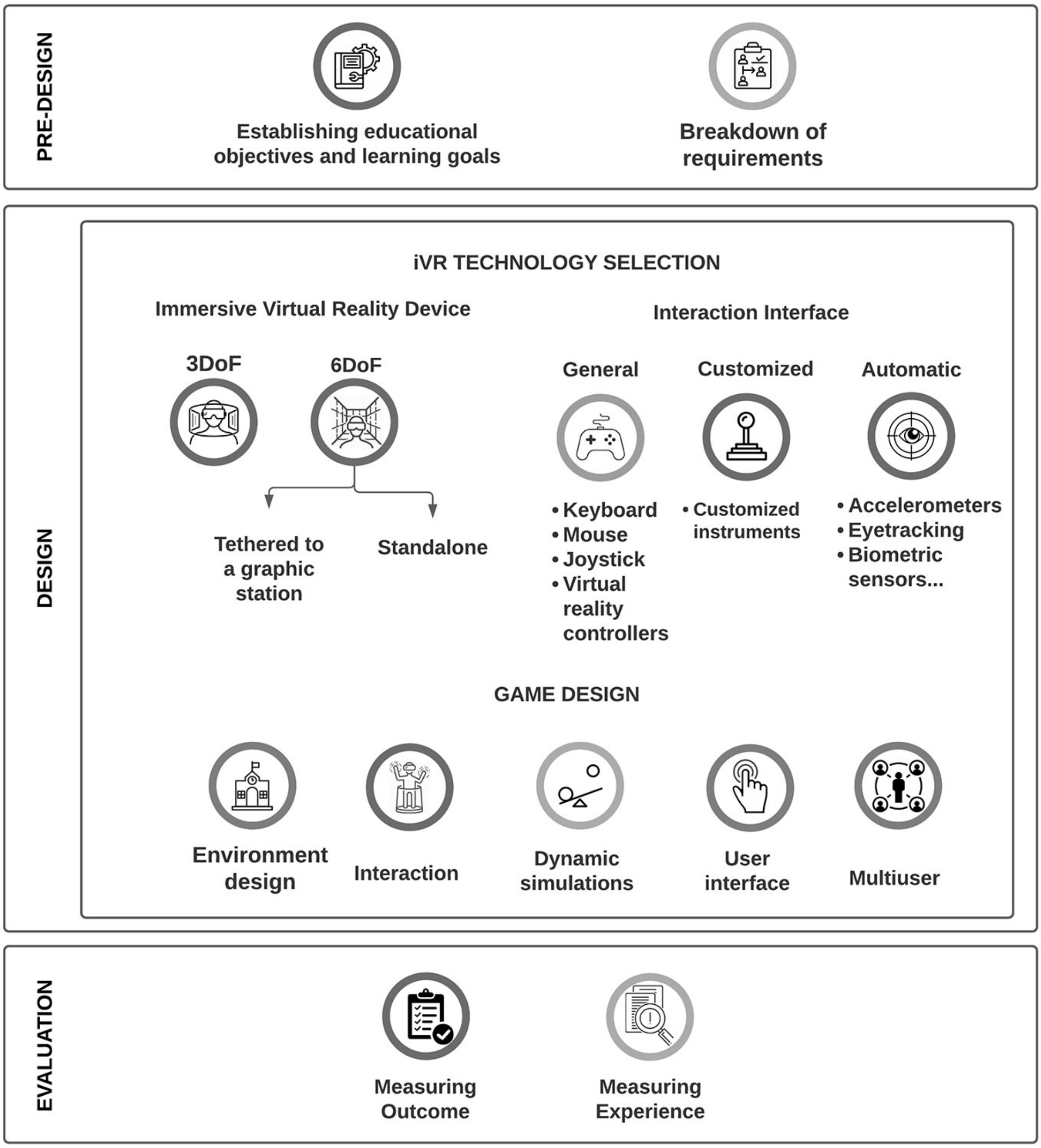

FIGURE 5: FLOW CHART FOR THE DESIGN AND IMPLEMENTATION OF A VRIE.

In the second stage, the *design*, some questions have to be answered:

- Which iVR technology is best suited for the proposed application? As described above, there is a wide variety of devices with substantial differences in functionality, portability and price. The interaction interfaces are subdivided into: general, customized and automatic. The general ones include keyboards, mouse and IVR controllers that are normally included with each HMD. The second group refers to interfaces customized by the application developer, usually found in educational experiences related to medical fields, which enhance the user's ability to learn specific tools. The third group includes all sensors that collect data automatically; they can be integrated into HMDs, such as accelerometers or eye-tracking sensors, or adapted to the user, such as biometric devices. These sensors are essential tools that provide insight into the user's performance and decision-making capabilities.

- Which is the best game design for this application? In the learning experience, the learner has to select, organize, and integrate information within a limited working memory, so the iVR learning environment should be directly designed to support these processes. For example, interactivity should be designed to be easy to use; a well-designed learning curve should be developed for novices to the iVR technology; and preferably a game structure that offers genuine game play, rather than quiz-like questions and answers, should be created. A balance between immersion, freedom and comfort must be sought in the design of an iVR experience. In addition, the design should take account of incorporating game-based learning elements that support the motivational needs of competence, autonomy and relatedness, so that the motivation and the engagement of the student is maintained. Finally, the application should be designed in such a way that it can be modified, customized and easily updated by the instructors, so they can fit the needs to their individual classes and students. An advanced graphical application programming interface (API) for game engines is usually employed. Unity 3D and Unreal Engine are the two most common game engines in IVR. These two engines include tools such as physical force simulators, graphics engines (responsible for generating 3D graphics using methods such as rasterization, ray tracing, *etc.*) and interaction modules to integrate devices such as IVR controllers, custom interfaces or sensors in a simple way in the experiences.

Finally, the third stage consists of the *evaluation of the iVRLE*. The evaluation should take into account which are the key factors to be evaluated and how are they can be better evaluated. If iVR is to gain wide-spread acceptance as a reliable pedagogical method, it must demonstrate that it can confer a tangible benefit in terms of learning outcomes over less immersive and traditional teaching methods (Mikropoulos & Natsis, 2011). It has been observed that most studies on iVR as a learning tool have no well-defined evaluation method or perform no comparison with other methods of education (Radianti et al., 2020). Most studies used only one of the following evaluation procedures: questionnaires, user interviews, data recording, and direct user observation. A combination of two of these procedures, especially questionnaires and indicators extracted from data recording, would also increase confidence in the results, especially if standardized questionnaires were used. This strategy would increase the validity and reliability of the conclusions, as previous studies have pointed out (Petri & Gresse von Wangenheim, 2017).

1.4 Advantages of iVR for learning

Despite the recent democratization of iVR technologies, there is already a rich history of research into immersive virtual reality and its educational applications. Different key features have been identified in these works as advantages of iVR for learning enhancement:

- *Motivation and engagement*: Maintaining learner interest and motivation is a challenge for any educator. A motivated learner will be more engaged and more determined to try to understand the learning material, as well as more resilient to potential obstacles to its understanding (Parong & Mayer, 2018). This is a process in which technologies such as 2D multimedia systems (videos, touch screen devices or computers) have already been incorporated into the classroom. Although these technologies are typically described as impersonal, unsociable, and with associated deficits in learning by transfer (Moser et al., 2015). iVR used as an educational tool can overcome most of the limitations of these technologies. Most investigations measure motivation and engagement and conclude that the use of iVR leads to increased interest and engagement when compared to conventional learning environments or other 2D multimedia systems (Makransky, Borre-Gude, et al., 2019; Radianti et al., 2020).
- *Interaction*: there are higher levels of interaction with iVR than with conventional educational methodologies. Traditional education has usually been language-based, conceptual and abstract; characteristics that compromise the implementation of practical learning. VR supports 'doing' rather than only observing, which leads to a constructivist approach, where students learn through interaction and even collaborate with other students. In this way, students can experiment, investigate and obtain instant feedback in a personalized experience that can improve learning (Roussou & Slater, 2017). They can learn experientially and proceed at their own pace. iVR offers enhanced learning through active participation, in which learners create their knowledge through practice, using motor and cognitive skills and receiving frequent feedback. This makes learning content easier to connect to the real-world context (Papanastasiou et al., 2019). iVR technologies can complement classroom teaching rather than replace it, with technologies like VR being particularly useful for teaching practical tasks, while virtual laboratories can

offer advantages over traditional methods, such as providing greater flexibility for conducting experiments.

- *Impossible becomes possible*: VR applications can be used to transform abstract concepts into concrete perceptions and experiences and to obtain more meaningful knowledge (Chen, 2016). Processes that occur at both microscopic and macroscopic levels are not easily observable in real life can be examined in detail in iVRLE. iVR can create a window to another place and time, so that far off and inaccessible places and sites may be discovered that no longer exist today. iVRLE can simulate complex, dangerous or very expensive experiences, allowing students to learn in a safe environment (Kwon, 2019). In addition, because it is a simulated environment, students can understand the potentially dangerous consequences of failure to follow procedures properly without physical damage to either equipment or casualties (Potkonjak et al., 2016). iVR also means that the student can have access to specialized equipment that not all educational institutions can incorporate and provides complementary benefits such as greater flexibility, by allowing the student to complete or repeat the exercises as many times as necessary (Pirker et al., 2017).
- *Soft-skills training*: iVR can be used for empathy training, enabling students to empathize with others and to broaden their range of perspectives and experiences beyond their normal spheres of interaction. Other soft-skills like pressure or time management can also find advantages of immersion capabilities of iVR.
- *Distance learning*: Likewise, as the COVID-19 pandemic has highlighted, there is a need for tools that facilitating e-learning and iVR has been shown to be effective in distance learning processes (Urueta & Ogi, 2020). The immersive nature of iVR helps block out other distractions, making students more focused and concentrated on learning objectives (Ibáñez et al., 2011).
- *Implicit learning*: some studies point to the knowledge acquired through the use of implicit learning (process whereby individuals absorb complex information without a conscious learning process and gain abstract knowledge through this process (Reber, 1989)) and the high efficiency of iVR experiences for the recall of spatial positioning.

TABLE 2: ADVANTAGES OF IVR FOR LEARNING

MOTIVATION AND ENGAGEMENT: Students learn best when they undergo a real experience or the experience is realistically simulated as in iVR experiences.
INTERACTION: iVR supports 'doing' rather than only observing, allowing students experiment, investigate and obtain instant feedback in a personalized experience that can improve learning (Roussou & Slater, 2017).
IMPOSSIBLE BECOMES POSSIBLE: VR applications can be used to transform abstract concepts into concrete experiences, simulate complex, dangerous or very expensive experiences, allowing students to learn in a safe environment (Kwon, 2019).
SOFT-SKILLS TRAINING: iVR empowers learners to empathize with others and broaden their range of perspectives and experiences.
DISTANCE LEARNING: iVR helps block out other distractions, keeping learners more focused on learning objectives (Ibáñez et al., 2011).
IMPLICIT LEARNING: learn complex information unconsciously and gain abstract knowledge through this process (Reber, 1989).

1.5 Limitations of iVR for learning

Despite the growing popularity of iVR due to the above-mentioned advantages, there are some limitations that should be considered when integrating iVR into an educational environment:

- *Hardware limitations*: despite the democratization of iVR technology over the last ten years, its high price is one of the main barriers to its implementation in the classroom. Even more so, considering that it is necessary to buy enough devices to satisfy the needs of a group. Likewise, the most realistic experiences require powerful workstations tethered to HMDs. In addition, any of these technologies are susceptible to malfunction and the risk of crashing increases as more students are involved in the iVR experience (Choi et al., 2016). Likewise, incorrectly adjusted HMDs can cause images and text to appear blurry. In addition, some iVR experiences can only be conducted on a specific HMD and are useless when the specific equipment is discontinued or becomes obsolete.
- *VR sickness*: It should also be noted that even current iVR technology can cause people to suffer from motion sickness and visual discomfort (Jensen & Konradsen, 2018). VR sickness can be referred to as a mal-adaptation syndrome

when exposed to real and/or apparent motion and can affect some participants, with symptoms strong enough for them to terminate the experiment abruptly at any point (Lawson, 2014). One of the most frequent technical factors causing VR sickness is system latency. These aspects are becoming progressively reduced with the new hardware technologies, so that nowadays fewer and fewer users are affected, but it is still a factor to be taken into account when creating an iVR educational experience.

- *Novelty effect*: The use of technology itself causes extraneous processing during learning, leading to worse learning outcomes (Allcoat & von Mühlenen, 2018). iVR is as yet a relatively new technology in classrooms and, for many learners, it is the first time they have used an HMD. The unfamiliar experience associated with wearing the headset, learning how to use the controllers in a specific way and the novelty of VR interfaces could be a source of extraneous cognitive load (Wu et al., 2013). Slow and progressive familiarization, visual clues, and guidance incorporated in the software should be used to help the user to overcome these limitations.

From a learning experience design point of view, iVR faces some constraints:

- *Finding effective iVR learning experiences:* the technical skills of most teachers are not sufficient to create their own iVR applications to foster learning. Therefore, they rely on previously developed content. It is important to find an application designed in such a way that it can easily be modified, customized, and updated by the instructors, so they can fit in with the needs of their individual classes and students. Also, these iVR experiences tend to be very short, because their development is costly in terms of both time and money; but short exposure times clearly limit the learning rate (Ritterfeld et al., 2004). In addition, these applications should be based on relevant learning theories and have clear educational goals and objectives that support the use of iVR. Finally, many of the iVR experiences aimed at improving learning do not use robust evaluation methods in their assessment. This problem already appeared in the first reviews on Virtual Reality applied to teaching ten years ago (Mikropoulos & Natsis, 2011). In many cases, the studies used no reference group at all, or established no comparison between the performance of the iVR experience and other learning methodologies. They are also often presented as isolated learning experiences and the target audience is often very limited in size. This lack of comparison or the limited size of testing groups is mentioned in similar reviews on the educational use of video games (Egenfeldt-Nielsen, 2006). Therefore, robust evaluation methods must be used to increase confidence in the results and to strengthen the use of iVR in the classroom.

- *Integrate iVR learning experiences into the educational program:* incorporating iVR as part of an educational program can be difficult and some teachers may be hesitant to use this new technology (Huang et al., 2016). It involves redesigning lesson plans and moving to a student-centred lesson plan. Hence, the teaching roles change, and the teacher becomes a promoter of knowledge and the student assumes a more active learning role (Youngblut, 1998). It is essential to examine the course curriculum and to determine where iVR can help and where other teaching methods are more appropriate. In addition, if the iVR experience or devices are difficult to use, it may discourage teachers from using them in their classrooms (Choi et al., 2016).
- *Student safety*: When using iVR, it is necessary to establish safe operating procedures. As the experience becomes more immersive and interactive, a larger physical space is required to use the equipment. Typical classroom settings often lack the facilities to use this technology safely. If this technology is used in confined spaces, students are at risk of physical injury, such as bumping into each other and into the walls. Safe operating procedures need to be established before using this technology in a school setting.
- *Mixed evidence:* Although a large variety of research literature points to the fact that the use of iVR experiences improves learning, it is also fair to highlight the studies that found no positive effects. Moreover, two studies reported negative effects of using iVR on learning even when learners were reporting very high satisfaction rates (Makransky, Terkildsen, et al., 2019; Parong & Mayer, 2018) and some others presented no effects on learning outcomes (Madden et al., 2018; Meyer et al., 2019; Moro et al., 2017; Smith et al., 2018; Stepan et al., 2017). This fact only underscores the need for further research on the role of the design elements and learning contents to explore the potential of iVR to enhance learning.

Table 3: Limitations of iVR for learning

HARDWARE LIMITATIONS: iVR technologies remain relatively expensive, and some experiences can only be delivered in a specific HMD.
VR SICKNESS: even current iVR technology can cause people to suffer from motion sickness and visual discomfort.
NOVELTY EFFECT: The use of iVR technology itself causes extraneous processing during learning, which can lead to worse learning outcomes (Allcoat & von Mühlenen, 2018).
FINDING EFFECTIVE IVR LEARNING EXPERIENCES: is difficult to find applications designed in such a way that it can be modified, customized, or updated easily by the instructors so they can fit in the educational program.
INTEGRATE IVR LEARNING EXPERIENCES INTO THE EDUCATIONAL PROGRAM: identify where iVR can help and where other teaching methods are more appropriate.
MIXED EVIDENCE: no clear advantage was observed in some of the studies and others were not statistically significant with respect to the use of iVR compared to conventional methodologies.

2. Motivation and goals

One of the characteristics of a Thesis based on a compendium of publications is the lack of a single motivation: as many motivations as publications are included in it. In general, this Thesis details research into the use of iVR technology as a learning tool at undergraduate level. This chapter summarizes the main motivations and objectives of the research conducted in this Thesis.

How to use iVR and how well it will be able to achieve its potential as an educational tool has yet to be determined, since this technology is an emerging educational technology still in its infancy (Bell & Fogler, 1995; Southgate, 2019). This fact opens up significant challenges and opportunities for the development of applications that enhance learning. Therefore, a full understanding of the potential effects of this technology is critical when applied to the learning process, more specifically, how will iVR be experienced and implemented in educational settings and what aspects of this technology can be useful for enhanced learning. Unfortunately, due to the novelty of iVR, a large part of the current research into iVR is either not very rigorous, giving no consideration to human-technology interaction, or conveys no pedagogical information. The results of this research can help educators, researchers, and iVR developers who want to use iVR to enhance learning.

The objectives pursued in this Thesis to address the problems described above are:

- Goal 1: *critical analysis of the literature on iVR for learning purposes*, to provide a deeper understanding of: 1) how to benefit from its use; 2) evaluate the possibilities and limitations of iVR learning experiences nowadays; and 3) identify the barriers to the incorporation of iVR in educational programs.
- Goal 2: *design of effective iVR learning experiences*. These experiences are developed with the intention of helping students to achieve the planned learning outcomes. This goal is required because most of the existing publications do not consider or explain how they design the iVR learning environments they use. Therefore, literature on how to develop effective learning experiences in iVR is scarcely available, while the design of the iVR experience is a key factor for a successful learning process.
- Goal 3: *assessment of the effectiveness of iVR learning experiences designed in Goal 2*. This assessment will be achieved by identifying and determining whether an iVR experience is more effective than conventional teaching procedures. The study of the effectiveness of iVR can be approached from four major points of view: *What works, When it works, How it works and What happens* (Mayer, 2011). This Thesis addresses the question *What works?* referring to the learning effects of using an iVR experience versus learning in a non-immersive environment. Assessment involves specifying the learning objective and developing ways to measure the learning outcomes that are valid,

reliable, objective and referenced. To that end, it is important to use an evidence-based research method that includes: 1) a significant question that can be empirically investigated, such as: will the use of an iVR learning experience result in better academic learning than receiving the same content through conventional media?; 2) the use of methods that permit direct investigation of the question. The scientific rigor of iVR research and its effectiveness in experimental comparisons depends on the use of an experimental control in which the treatment and the control group receive identical treatments except for the one element that is manipulated (in this case the delivery medium: iVR or conventional media). 3) Random assignment between control and treatment group. 4) Use of appropriate measures, as it is crucial to have relevant and valid measures of learning outcome, including means, standard deviation and sample size.

These objectives are intended to approach both the advantages and the limitations of the educational applications of Immersive Virtual Reality for learning using three perspectives: analytical, through the examination of iVR experiences from a learning point of view; practical, with the development of effective iVR learning experiences; and, evaluative, with evidence-based analysis of previously created iVR experiences.

3. Results

The scientific results of this Thesis, presented as different subsections that correspond to scientific publications previously published in journals, are detailed below. A brief summary of the objectives and motivations of each publication is included at the beginning of each subsection.

Result 1: A review of immersive virtual reality serious games to enhance learning and training

Result 2: Advantages and limits of virtual reality in learning processes: Briviesca in the fifteenth century

Result 3: Immersive virtual-reality computer-assembly serious game to enhance autonomous learning

Result 1: A review of immersive virtual reality serious games to enhance learning and training

In this journal paper, a critical literature review is presented on iVR for learning purposes. Its objectives are: 1) to instill a deeper understanding of the benefits associated with using iVR technologies as learning tools; 2) to evaluate the possibilities and limitations of iVR learning experiences today; and 3) to identify what the barriers are to its incorporation in educational programs. This work aligns with Objective 1 of this Thesis and uses an analytical approach to reveal the advantages and limitations of educational applications of Immersive Virtual Reality for learning. The study provides the foundation for subsequent research into the development of iVR experiences, providing recommendations for the improvement of these tools and their successful application for the enhancement of learning.

Title: A review of immersive virtual reality serious games to enhance learning and training
Authors: Checa, David; Bustillo, Andres
Type: Journal
Published in: Multimedia Tools and Applications, 79: 5501–5527 (JCR: Q2, SJR: Q1).
Year: 2020
Keywords: Virtual reality, Learning, Systematic literature review, Serious game, Evaluation
DOI: https://doi.org/10.1007/s11042-019-08348-9

Abstract

The merger of game-based approaches and Virtual Reality (VR) environments that can enhance learning and training methodologies have a very promising future, reinforced by the widespread market-availability of affordable software and hardware tools for VR-environments. Rather than passive observers, users engage in those learning environments as active participants, permitting the development of exploration-based learning paradigms. There are separate reviews of VR technologies and serious games for educational and training purposes with a focus on only one knowledge area. However, this review covers 135 proposals for serious games in immersive VR-environments that are combinations of both VR and serious games and that offer end-user validation. First, an analysis of the forum, nationality, and date of publication of the articles is conducted. Then, the application domains, the target audience, the design of the game and its technological implementation, the performance evaluation procedure, and the results are analyzed. The aim here is to

identify the factual standards of the proposed solutions and the differences between training and learning applications. Finally, the study lays the basis for future research lines that will develop serious games in immersive VR environments, providing recommendations for the improvement of these tools and their successful application for the enhancement of both learning and training tasks.

Introduction

Sutherland described "The Ultimate Display" [146] as "a room within which the computer can control the existence of matter", clearly underlining the immense potential of technological innovation to enhance the learning rates of almost any professional skills training. Teaching has therefore to adapt itself to this new technology, quite unlike traditional oral-based education that is mainly focused on abstract rather than practical learning skills, resulting in a weaker and less robust understanding of the topic [12]. However, Virtual Reality (VR) environments have been excluded from educational settings, due to the high cost of VR equipment. Their usage over the past 50 years has been restricted to military applications and research institutes [162]. Throughout that time, research objectives have been focused on technological issues: the development of VR-environments and both hardware and software [13, 162]. In parallel, educational researchers have described any educational experience that introduces the user to visual and auditory experiences as a "virtual world". The reviews on these topics have underlined both learning [72, 120] methods that employ conventional computer graphics on a monitor or other 2D displays. This concept of virtual worlds is nowadays categorized as low-immersive VR.

Some 15 years ago, high-immersive VR emerged with the development of devices that surround the user in large 3D viewing areas, such as the Head-Mounted Display (HMD) and the Cave Automatic Virtual Environment (CAVE) [15]. The development of those devices was accompanied by the first VR-environments applied to educational tasks in specific knowledge areas: mathematics, language, business, health, computer science, and project management [9, 37, 62]. The main reviews of these initial educational VR experiences outlined their two guiding principles: 1) the fascination among young people with new technologies, including the clear example of VR, suggests greater interest in learning in those environments [75]; and, 2) VR could facilitate a visual understanding of complex concepts [12] for students and reduce misconceptions [98].

This first generation of immersive VR devices was also applied to training. The high cost of VR equipment was no obstacle to the military that exploited the effectiveness of simulation exercises. VR-based simulations offered a secure space to conduct exercises that would otherwise be risky and costly in real life. [79, 109]. These devices were also tested in training for sports [69, 99] and especially in industry, where new employees receive 'risk-free' training in a virtual manufacturing scenario [84]. Finally, medicine and especially surgery are also considered promising fields for VR training [130].

At this stage in the incorporation of the VR learning environment into traditional learning methods, a debate emerged over which procedures could best achieve the perception of a user presence in the VR-environment. This feeling of immersion and presence is identified as a key factor for the enhancement of learning rates [98]. Presence might be defined as the immediate perception of the user of "being there" and a feeling of existing inside the virtual environment [143]. Presence is therefore a very subjective experience. Immersion can be defined as the technological fidelity of VR that the hardware and software can evoke [15] and it can be objectively evaluated. Immersion is therefore considered in this review as a better key objective for VR experiences than presence.

However, immersion and presence have only been key objectives of VR experiences nowadays, because of the improvements, over the last five years, in the quality of HMDs and their significant reduction in cost (*e.g.,* the launch in 2013 of Oculus Rift™ dk1). Moreover, the second bottleneck for the large-scale development of VR-environments, the software tools, was eased with the launch of the free versions of two powerful motor engines: Unreal Engine™ and Unity™. These new software programs have permitted the rapid development of user interactions with the VR-environment, opening the way towards the design of serious games in VR immersive environments.

However, although the VR-environment will produce the effect of immersion, a second element is required to achieve high learning rates: user interactivity with the VR-environment. The use of games is the natural way to achieve high levels of interactivity. Serious Games (SGs) are activities designed to entertain users in an environment from which they can also learn and be educated and trained in well-defined areas and tasks. Unlike traditional teaching environments, where the teacher controls the learning (*e.g.,* teacher-centered), SGs present a learner-centered approach to education. The trainee feels in control of an interactive learning process in an SG, thereby facilitating active and critical learning [140]. Different reviews have described the use of SGs in education and training. Malegiannaki [90] analyzed the use of spatial games in formal education related to Cultural Heritage issues, concluding that there were still many challenges relating to effective storytelling and the evaluation of the effect on student learning performance. Ibrahim [62] reviewed serious games in programming education, seeking to summarize findings on initial user perceptions towards the use of games in terms of motivation and learning. In the case of training, some researchers [48] have pointed to the most-effective final use of these experiences, which relates to the recreation of situations that could not otherwise be done in real life, including ethical dilemmas, and dangerous and even impossible situations, in terms of time and space. But all those reviews analyzed serious games which do not use immersive VR-environments, mainly because they have only very recently been launched.

While Virtual Reality Serious Games (VR-SGs) should improve user experiences and, therefore, knowledge acquisition, it is also clear that immersive VR-environments pose new questions on the best way to design efficient serious games for such environments. The main questions that present and future research will have to answer can be directly linked with the different stages of the definition of immersive VR-SGs shown in Fig. 1. In the first stage, two key items should be clearly defined before creating immersive VRSGs: the target audience and the application domain. There are four key objectives for a VRSG: interaction, immersion, user involvement and, to a lesser extent, photorealism [127]. Each objective will play a different role depending on the target public and the application domain. In the second stage of VR-SG design, the materials necessary for the immersive VR-SGs are created and included in the VR-environment. Different questions can be addressed: which are the best technologies to be used for the construction of the VR-environment? Which is the best game design for a certain application? If a game experience is to be a meaningful experience for players, it needs to have certain basic elements. Interactivity should therefore be designed with clarity: the required inputs and outputs, the short- and long-term goals that shape the player's experience, a well-designed ramp for beginners to learn the ropes; and a game structure that offers genuine play, rather than quiz-style questions and answers.

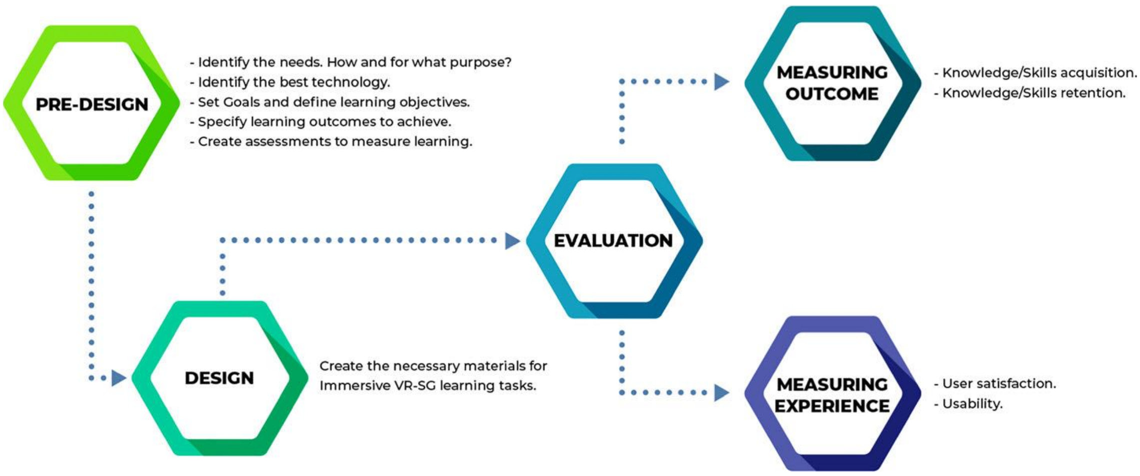

FIGURE 1: FLOW CHART FOR THE DESIGN AND IMPLEMENTATION OF IMMERSIVE VR-SGS FOR LEARNING TASKS:

Finally, the third stage consists of the evaluation of the VR-SG performance. The evaluation should take four different elements into account: 1) the key factors to be evaluated; 2) the way they are evaluated; 3) the number of individuals testing the serious game; and, 4) the existence or otherwise of a reference group. There is no clear consensus on how to evaluate serious games for educational and training tasks. For example, in the case of computing education [115], this fact has been clearly remarked: "As a result, we can confirm that most evaluations use a simple research design in which, typically, the game is used and afterwards subjective feedback is collected via questionnaires from the learners". The findings of Egenfeldt-Nielsen also showed that most educational games are evaluated in an ad-hoc manner. An evaluation mode that involves the administration of the game to very small validation groups of end users and then data collection, typically through the administration of a questionnaire [24].

Two final remarks should be added before finishing this Introduction. First, this review refers to Virtual Reality immersive serious games. Therefore, immersion should be a key factor in the research under analysis. Following this approach, many of the articles identified in a first stage of the survey were excluded from subsequent analysis, because they referred to 2D virtual reality, far removed from the concept of immersiveness that is relevant to the development of 3D HMDs.

Second, this review considers two different approaches to the learning process: the acquisition of new knowledge and the development of new skills. While the first has traditionally been seen as a combination of theory and problem-solving capability, the second has been directly related to practical skills and decision-making ability. However, there is no clear difference in the nature of the final process: learning. Therefore, this review considers both educative and training approaches to the learning process, even though they are analyzed separately, because the VR-SGs listed in the bibliography are carefully thought out, designed and evaluated from different perspectives.

Survey

Methodology

The methodology followed in the literature review was composed of four stages, as shown in Fig. 2 (educational results in bold and training results in italics). First, a search in the databases was performed with the keywords ("virtual reality" OR "head-mounted display") AND (education OR learning) for educational papers, and ("virtual reality" OR "head-mounted display") AND (training) for training papers. Two interdisciplinary research databases were used, to ensure an exhaustive search: SCOPUS and Web of Science, both identified as suitable databases for serious games searches [24]. The search was conducted in July 2019. Secondly, some additional references cited in the selected literature were considered, in an example of a snowball effect, as their titles clearly reflected their suitability for inclusion in the survey. Finally, the survey was extended to industrial magazines, VR/AR associations and technical congresses closer to the industry (*e.g.* the IEEE International Symposium on Mixed and Augmented Reality), to identify industrial efforts to recreate VR simulators for training tasks. But most of the research from those sources contained no quantitative evaluations and was not, therefore, considered in this survey. So only 3 papers, from among the total of 52 articles identified from these sources, could be added to the final survey. Having filtered out all duplicated papers, 6751 and 4432 articles were considered for the educational and training categories, respectively. Then, their abstracts were read, and irrelevant papers were removed considering the objective of this review. Most of the articles were excluded from the survey, because the core of their work referred to 2D virtual reality, far apart from the concept of 3D immersivity in relation the development of 3D HMDs. In any case, the search was not restricted to new 3DHMDs, so some articles on CAVEs and first-generation 3D HMDs were considered. Then, those articles that focused on VR solutions designed to enhance the recovery of patients from different illnesses and post-operative complications were filtered out, because their evaluation was focused on health indicators, rather than on learning and skills improvement. A total of 171 and 235 relevant articles were left, following that filtering process, under the two categories of education and the training, respectively. In the fourth and final stage, the full text of each remaining article was analyzed and the articles with no final-user performance evaluation of the virtual environment were filtered out. In all, 68 [1, 3–8, 10, 11, 18, 26, 28–30, 33–36, 40, 45, 46, 49, 51, 60, 63–68, 76, 80, 81, 83, 86–89, 94, 97, 101, 102, 104–106, 110–113, 117, 118, 121–123, 127–129, 132–134, 138, 142, 144, 149, 150, 153, 156, 160, 164] and 67 [2, 10, 14, 16, 17, 19, 21–23, 25, 27, 31, 38, 39, 41–43, 47, 50, 52–59, 61, 70–74, 77, 78, 82, 85, 91–93, 95, 96, 100, 103, 107, 108, 114, 116, 119, 125, 126, 131, 135–137, 139, 141, 145, 147, 148, 151, 152, 154, 155, 157–159, 161, 163] articles were considered for both surveys, representing a good balance between education and training. This balance was unexpected, because training is only one sector of education as a whole and no immediate explanation was found. Interestingly, other authors have also found similar balances between training and learning, for instance in application to project management software [24]. Although there was an important overlap between the articles of both categories in previous stages of the survey process, no manuscript can be considered in both categories at this final stage. The complete list of these manuscripts with their different classifications is provided in the supplementary material. The sample size in this review is comparable to reviews on similar topics, such as the 102-paper review of serious games for software project management [24] and the 129-paper review of empirical evidence on computer games [37]. It is also larger than other studies that analyzed virtual educational environments (53 papers) [98] and the effect of spatial games for cultural heritage (34 papers) [90].

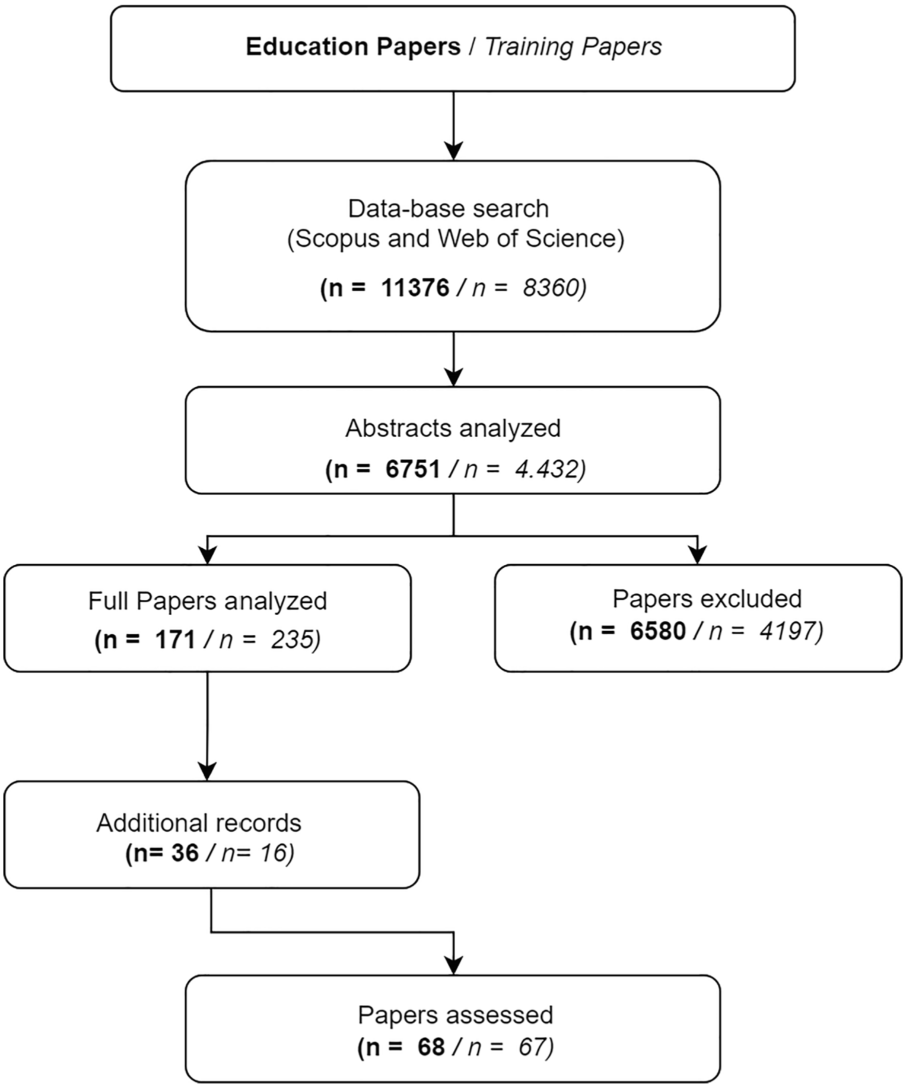

FIGURE 2: SCHEME OF THE REFERENCES SURVEY PROCESS

Data distribution

Some general ideas on VR-SGs can be directly extracted from the data on year of publication and the main congresses and journals in which the work was published.

Figure 3 shows the temporal evolution of the selected references. As expected, the launches of both VR hardware and software have, since 2015, boosted the number of publications on these topics, while a progressive short-term increase in such publications is still to be expected, although 2018 was an exception in this trend. The low number of articles in 2019 is directly related to the date of survey: before the annual conferences on these topics and after the publication in 2018 of only the first issues of the relevant journals. Although the growing trend is more stable in the training field, this result could change in the short term and further analysis of its evolution over coming years will contribute to a coherent conclusion.

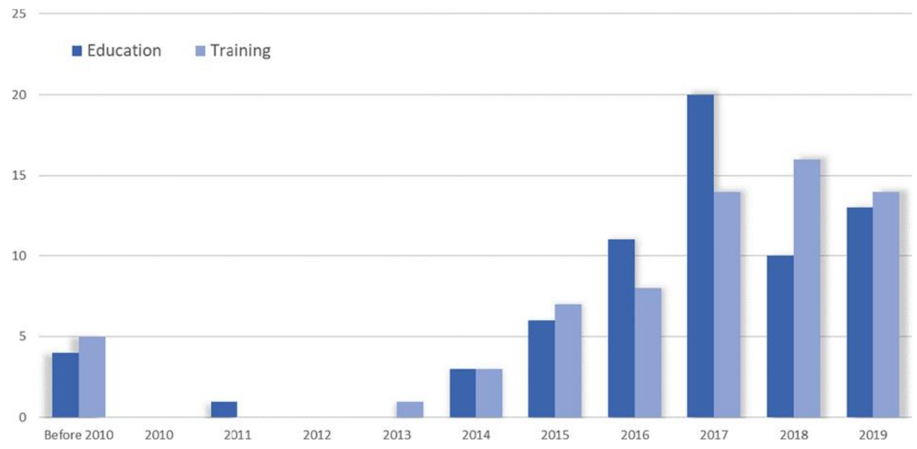

FIGURE 3: TEMPORAL EVOLUTION OF THE PUBLICATIONS ON VR-SGS

Finally, Fig. 4 shows the distribution of the articles between journals and scientific conferences. The information leads to the direct conclusion that there is a preference for publishing training applications in journals, while educational applications are mainly resented at conferences. If a deeper analysis is done to identify the preferred journals and conferences, the result shows the absence of any established publication forums for VR-SGs. The main congresses detected in the survey for educational applications were: AHFE -Conference on Applied Human Factors and Ergonomics- (3 articles), CHI PLAY -Play, Games and Human-Computer Interaction- (2 articles), AVR -Conference on Augmented Reality, Virtual Reality and Computer Graphics- (2 articles) and EDUCON -IEEE Global Engineering Education Conference Engineering Education. Through Student Engagement- (2 articles). The main congresses for training applications were: VAMR -International Conference on Virtual, Augmented and Mixed Reality- (3 articles) and MELECON -Mediterranean Electrotechnical Conference- (2 articles). Likewise, the preferred journals for educational applications in the survey were: Behavior & Information Technology (3 articles) and Virtual Reality (2 articles). The preferred journals for training applications were: IEEE Transactions on Visualization and Computer Graphics (3 articles) and Mathematics, Science and Technology Education (2 articles). The major conferences and journals on these topics therefore included only 29% and 26% of the articles in the survey, respectively. The main reason for this result is the novelty of the topics, which fall outside the scope of established journals with high-impact scores in the Journal of Citation Reports, added to which the conferences on these topics are very recent.

Analysis of the article

The results of both surveys are arranged in this section under application domains and target public, technological implementation, game design, performance evaluation procedures and results. The aim of this analysis is the identification of factual standards or differences between the proposed solutions in both fields.

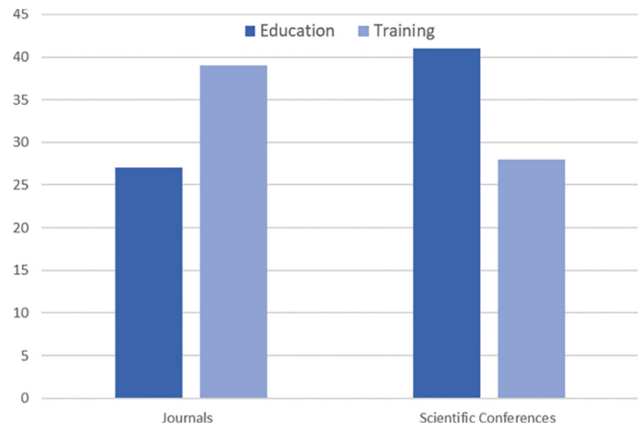

FIGURE 4: DISTRIBUTION OF ARTICLES ON VR-SGS BETWEEN JOURNALS AND CONFERENCES

Application domain and target public

The target audience of the studies was classified into three classes: general public, students and professionals. Figure 5 presents the respective percentages of the articles in the survey that belong to those three classes. For a deeper analysis, the professionals were classified into four subclasses in the training case: teachers, health services, industry, and sports professionals.

Three conclusions may at first sight be extracted from this figure. Firstly, around one fourth of the studies (22% for educational games and 25% for training applications) belong to the class "general public". Most papers related to VR-SGs for museums and other types of exhibitions belong to that class, where the final user is unrestricted; the papers that study the technological issues of VR and SGs also belong to this class. Secondly, more than two thirds of the educational applications are focused on students at different levels, as there is a natural correlation between students and education. There are studies for all the learning stages, from kindergarten to university, with a higher proportion of studies focused on undergraduate students. A clearly lower proportion of students is found in the training survey; most of them refer to medical applications and focus on training students in different hospital operations, see Fig. 6. Thirdly, almost half of the SG-VRs for training are specifically designed for professionals, mainly in industry and medicine, and less so in educational institutions and sports. It is interesting to note the small niche for VR-SGs to train teachers (*e.g.* related to the development of skills to detect bullying and to improve presentation skills).

Surprisingly, only medicine presents a significant quantity of articles in both categories (training and education). Medicine therefore appears to be a more mature domain for VR-SGs, because a broader range of final applications has been studied in that area. Unlike medicine, sports and industry only present training applications. As regards education, consideration is mainly given to either students or the general public, with undergraduate students playing a central role. Much remains to be done to find the best orientation of VR-SGs in the various

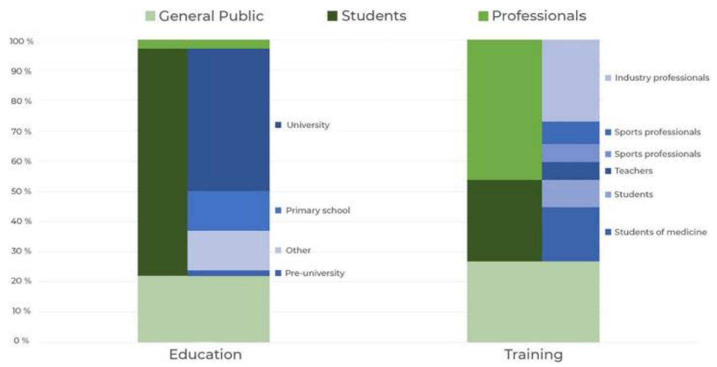

FIGURE 5: TARGET PUBLIC OF THE VR-SGS

final applications, as the immediate solutions of the pairs 'education-learning' and 'skills training' have only recently been extensively applied.

Technological implementation and game design

Different technical solutions can be selected for the same application, all the more so given the diversity of VR-SGs applications and with such different target publics, as observed in previous subsections. Usually, the technical solutions should be based on three choices: the visualization display, the game engine, and game typology. Figures 6, 7 and 8 show the selected HMDs, the game engine and the serious game typology presented in the survey for training and educational applications, respectively.

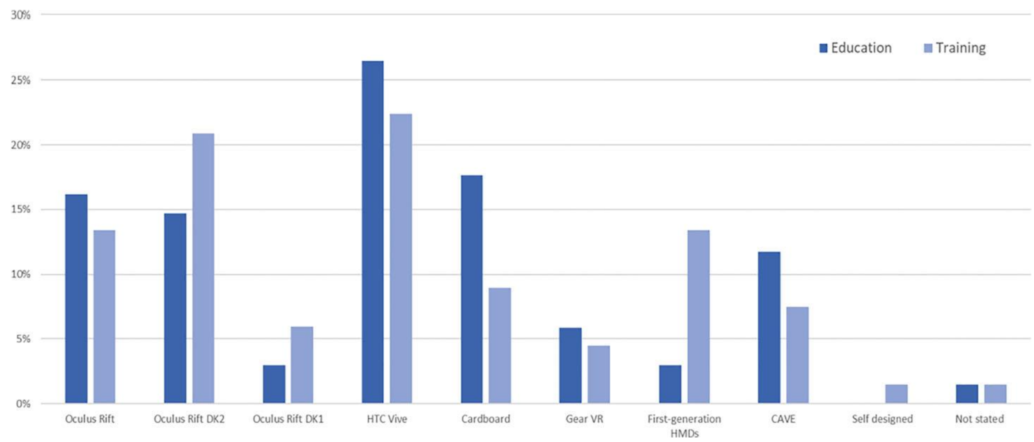

FIGURE 6: MAIN 3D DISPLAYS USED IN VR-SGS

Figure 6 shows the selected HMDs for training and educational applications. The two branded HMDs presented in the survey -Oculus Rift (in its three versions) and HTC Vive- are the most widely used, as well as cardboards connected to smartphones. The least recent articles of the survey used Sony HMZ-T1, Nvis nvisir sx111, and Emagin z800 HMDs; these HMDs are clustered in the graph, in Fig. 6, under the class "First generation of HMDs".

Figure 6 shows that Oculus Rift is the most common HMD (>40% of the cases), while HTC Vive is used in around 25% of the applications. The other 35% of applications in use are: 1) low-immersion solutions such as cardboards or Gear VR; 2) very expensive solutions (i.e., CAVEs); and, 3) self-designed or not stated in the article.

Figure 7 shows the selected game engine for both training and educational applications. The game engines presented in the survey were the most widely used in the gaming industry at the time of this research: Unity 3D and Unreal Engine over the last 3 years. XVRtechnology, Worldviz and Ogre3D were mainly used in older works and are clustered in the class "Old game engines". Figure 7 shows that Unity 3D is the preferred solution, while no other motor engine exceeds 15% of mentions in the references. The most likely reasons for the widespread use of Unity 3D are its low cost and its ease of implementation with HMDs. Besides, a quarter of all the studies (25%) contain no statement of which game engines were used. They usually omit any reference to the development of the VR-SG, limiting themselves to its applications. These VR-SGs were developed by an external provider, so it may be assumed that the researchers were only interested in the application of the VR-SG to certain well-defined tasks and its effects. Finally, although the difference between educational and training solutions was not significant, the educational applications presented a higher use of Unity 3D than the training applications. The articles that describe the use of Unreal Engine were presented over the past three years, a period that coincides with its conversion to free software, which may point to stronger growth in the future for this software that stands out for its photorealistic capabilities, a key factor for training purposes for certain SGs [30].

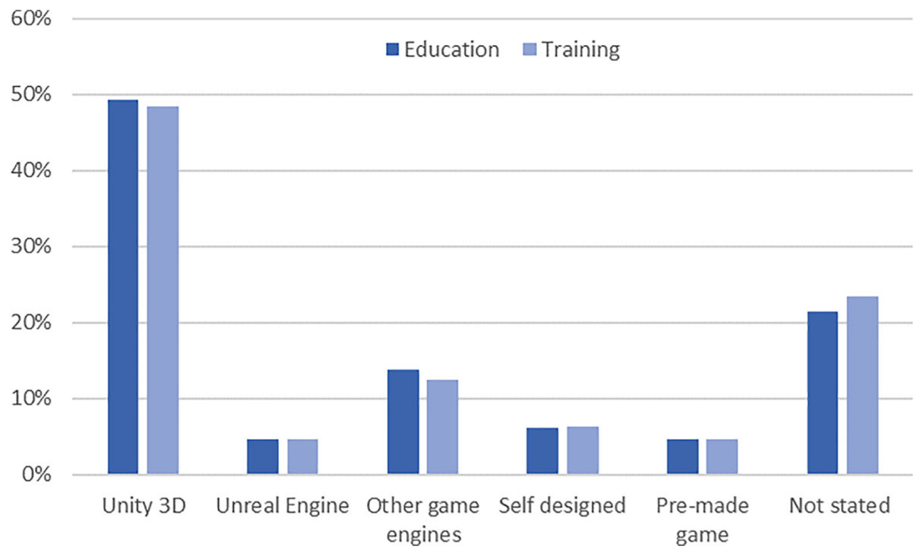

FIGURE 7: MOST POPULAR GAME ENGINE FOR VR-SGS

Figure 8 shows the game typologies, both for the training and the educational applications, divided into four classes: explorative interaction, explorative, interactive experience and passive experience. Explorative interactions are those games that allow the user to explore and to interact freely with the virtual environment. A more restricted solution is the explorative experience, which allows free exploration of the virtual environment, although no direct interaction. The interactive experiences permit user interaction with the environment, but no free movement through it. Finally, the most restricted solution is the passive experience, in which user interactivity and movement are very limited.

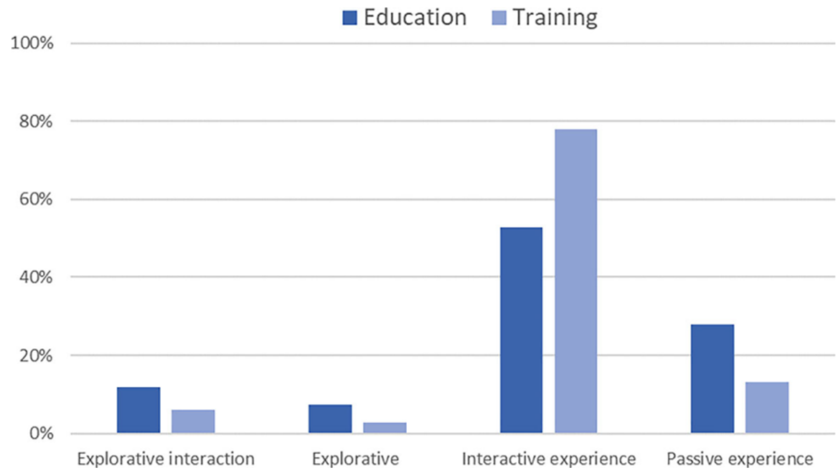

FIGURE 8: TYPOLOGY OF SERIOUS GAMES

The most common solution, especially for training, is the interactive experience, as shown in Fig. 8. This solution is more affordable than explorative experiences that require the complete development of the VR-environment. In the case of interactive experiences, the VR-environment will only have to be developed in high resolution in the areas where the user is permitted, while any secondary area can be roughly modelled, saving costly human and computational resources [29]. Along the same lines, the number of explorative experiences is very limited, due to their high cost. Besides, no clear use of explorative experiences for both learning and training is evident, because the user has no clear objective in the VR-environment. They are therefore mainly used as complements rather than core educational resources in the educational process. There are very few passive experiences and they are clearly connected to the use of cardboards (see Fig. 9), in view of the useful interactive and explorative experiences provided by those devices, despite their technical limitations. Although, these solutions are not very common, they are presented here because of their very low economic cost for both creation and implementation in the classroom.

The analysis of Fig. 8 leads to the conclusion that the interactive experience is the preferred VR-SG for training and education, due to its balance between costs, technological development, immersive feeling, and potential to stimulate learning and skills improvement. Explorative experiences might be more suitable for research tasks and, although still too expensive for mass use, show a promising potential for future growth.

Figure 9 presents a detailed analysis of the correlation between the different HMDs and the VR-SGs typologies. It compares the use of each kind of 3D Display in the different typologies of VR experiences. This figure shows that explorative and explorative-interaction VR-experiences are only developed for CAVEs and high-quality HMDs such as Oculus Rift and HTC Vive, because of the higher computational capabilities of the workstations that control these devices. In contrast, passive experiences, as mentioned, are clearly connected to the useful interactive and explorative experiences achieved with cardboards, despite their technological limitations.

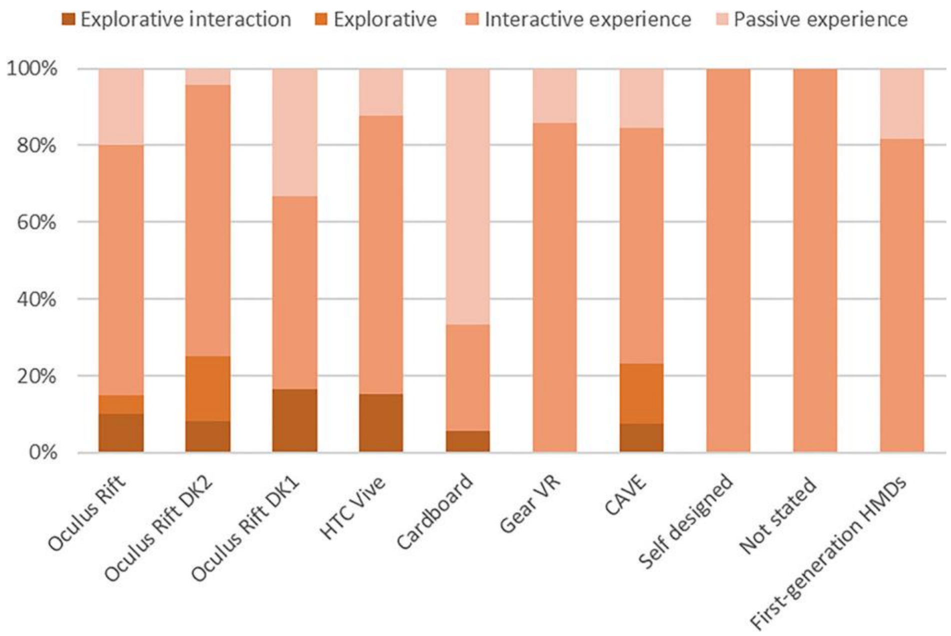

FIGURE 9: 3D DISPLAY TYPE DISTRIBUTION FOR EVERY TYPE OF VR EXPERIENCE

Performance evaluation

As previously outlined in the Introduction, one of the most conflicting issues in the use of serious games and VR-environments for education and training is the evaluation of the learning experience. Four different elements should be considered for this evaluation: 1) the key factors that should be evaluated; 2) the way they are evaluated; 3) the number of subjects that test the serious game; 4) and, the existence or otherwise of a reference group.

Regarding the first point, five different key factors were identified from the surveys: user satisfaction, learning rate, skills improvement, immersion and usability. Figure 10 shows the proportion of studies that evaluate these key factors. User satisfaction is not included in this figure, because all the selected articles in the survey evaluated it besides other key factors. As with the target audience, a significant difference between training and educational applications was noted: the educational applications were mainly focused on knowledge acquisition, while the training applications were designed for skills improvement. Despite this clear trend, some educational applications were also focused on skills improvement and some training applications were for knowledge acquisition. In any case, the evaluation of both skills improvement and knowledge acquisition is balanced in the survey, leading to a new question: are VR-SGs equally good for both tasks or is it just a consequence of a balanced survey between training and educational applications? Finally, studies focused on immersion and usability were very rare, although both factors could play a main role in the learning rate, as previous studies have stated [32]. It may therefore be concluded that the researchers considered two key factors -user satisfaction and a key factor directly related to the objective of the experience (whether learning rate or skills improvement)-. However, other key factors such as immersion and usability, which have a direct correlation with a successful experience, were not considered.

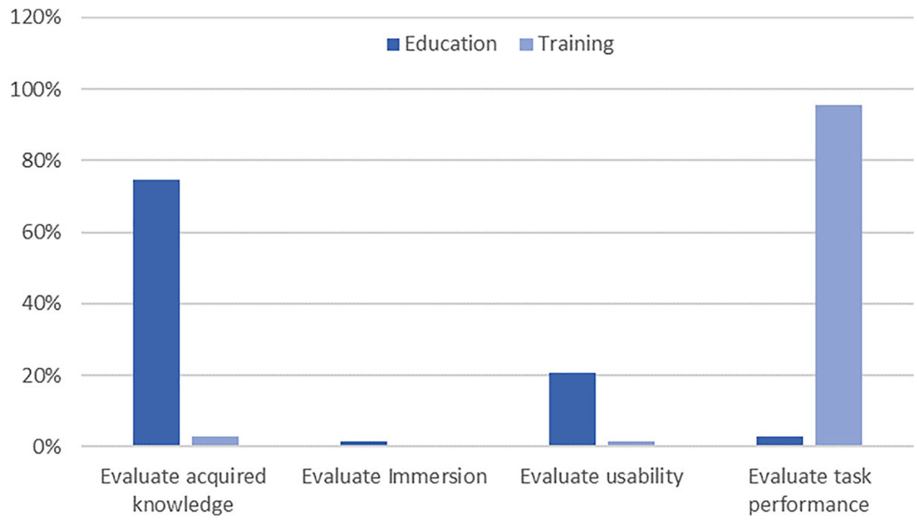

FIGURE 10: KEY FACTORS EVALUATED FROM THE VR-SGS PERFORMANCE

In addition, the type of evaluation can generate different results, if it is not performed in a standard way. Figure 11 shows the different methods used to measure the key factors: questionnaires, interviews with users, data recordings, and direct user observation. Figure 11 shows that the questionnaire is the most common solution to evaluate knowledge acquisition in educational applications.

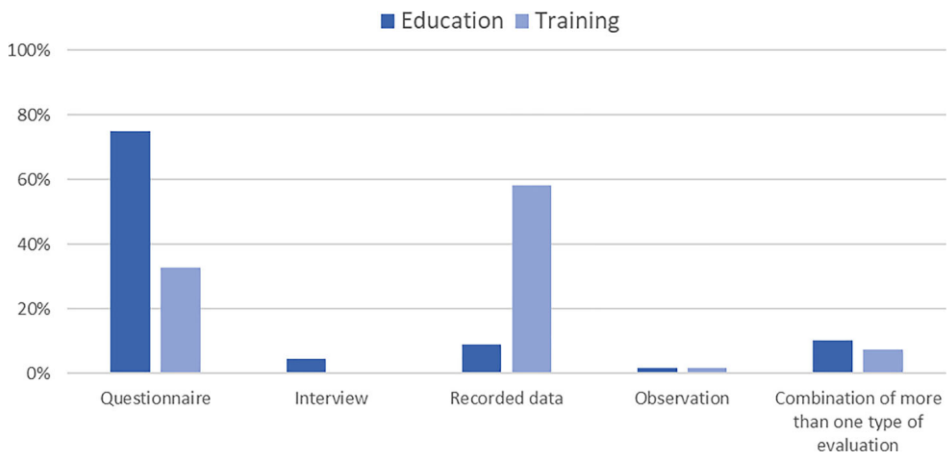

FIGURE 11: TYPE OF EVALUATION IN VR-SGS EXPERIENCES

The training applications showed a balance between the use of questionnaires and metrics on user experiences directly extracted from the recorded data. The use of the other two types of evaluation -interview with users and direct observation of the user- was very rare, as was the simultaneous use of more than one type of evaluation. In the case of the recorded data, the most common indicators were: 1) physiological data directly correlated with the proposed task, mainly in relation to medical applications; and, 2) the game score in educational applications. This group of metrics appears to be a more objective source of information than questionnaires.

Finally, the number of subjects that test the serious game will add weight to the statistical significance of the conclusions of each study. Figure 12 shows the size of the target group that tested the VR-SGs. There is a trend in the educational studies to use larger target groups than in the training studies, perhaps because the number of students available during the evaluation stage of the study was higher than the number of professionals (*e.g.* a degree module can have more than a hundred students in a small-medium university, while a medium-sized hospital may have fewer than 20 cardiovascular surgeons). In any case, the size of the target group was very limited compared with other educational applications, as in the case of SGs for teaching computing [115], where the mean average size was around 50 students. One reason might be due to the high average cost of hardware for VR-environments compared with more traditional learning methodologies.

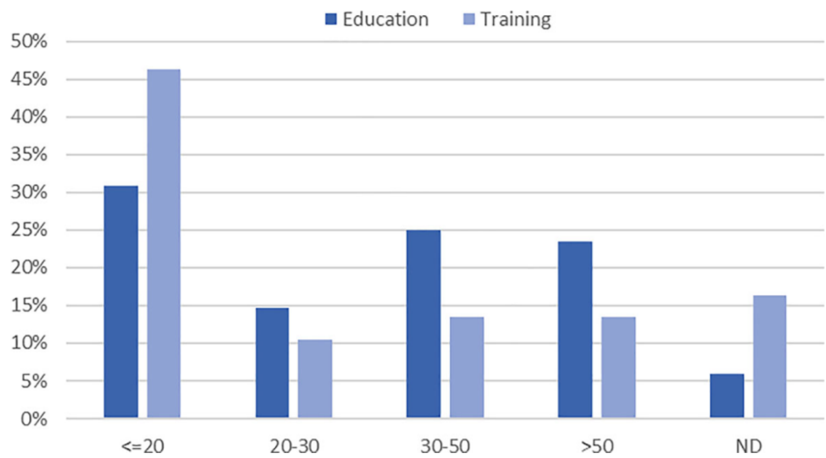

FIGURE 12: VR-SG EVALUATION GROUP SIZES

Results of the performance evaluation

There is one common conclusion presented in all the articles under analysis: user satisfaction is higher with the VR-SG experience than with other learning methodologies. This conclusion justifies the guiding principle that higher learning rates and skills improvement can be expected from VR-SGs (implying greater engagement, interest and motivation), in comparison with traditional learning and training methods. However, this line of reasoning may only be true in some cases and all possible scenarios should be scientifically validated.

Following this first general conclusion, in each article the pros and cons of the selected technology and methodology are discussed for the corresponding final application. From this discussion, the real value of each article can be understood. Table 1 shows the main conclusions in relation to each of the articles (after removing the conclusion on the increased overall satisfaction with the VR experience). The first three rows refer to positive results: VR-SGs increased the learning rate or improved certain skills compared with other learning or practice techniques. The studies with positive results were classified at three different levels. Item number 1: studies that provided well justified conclusions. Item number 2: studies that showed preliminary results. Finally, item number 3: studies that showed potential results without sufficient justification. Consideration was given to the size of the target audience in this three-point classification and to the existence of a reference group that is taught or trained with a different methodology. These three rows (items number 1 to 3) account for 75% and 86% of the studies on education and training, respectively. Therefore, most of the studies arrived at the following conclusion: VR-SGs are a suitable tool for both educational and training objectives regardless of the technical solution.

Support for the use of VR-SGs in education and training was not forthcoming in all cases: no clear advantage for VR-SGs was observed in 6% and 5% of the studies compared with traditional methodologies. Item numbers 4 to 6 of Table 1 show the percentage of studies that achieved the same performance level for both the reference and VR-SGs group (item number 4), those that achieved worse results with the VR-SGs group (item number 5) and those that arrived at no conclusion (item number 6), mainly because of weaknesses in the experimental design. The proposed tasks for these VR-SGs should be analyzed in detail to understand those negative conclusions. In the educational field, two kinds of VR-SGs showed lower learning rates: those that shared supplementary medical knowledge with undergraduate students and those designed to impart abstract scientific concepts on the curricula of Bachelor degrees. Even though the studies demonstrated lower learning rates than traditional teaching methodologies, they also identified higher levels of motivation, engagement and interest among the students. Lower skills improvements were noted with VR-SGs rather than 2D-screen simulators, in the

Table 1 Results of performance evaluation

Item number	Conclusion	Education	Training
1	VR demonstrably enhances learning	30%	29%
2	Positive prospects of the research (preliminary study)	12%	21%
3	Learning potential confirmed (not compared with other learning methods)	33%	36%
4	VR equal to traditional method in the classroom	6%	0%

5	VR not acceptable to improve learning	6%	5%
6	No significant conclusions inferred	3%	0%
7	No measurement of enhanced learning or skills improvement	10%	9%

case of simulators for training, driving, navigation, and pedestrian behavior. Those lower levels of improvement might be due to the low levels of experience with HMD setups among users. Therefore, the use of VR-SGs still has to be optimized in relation to very abstract concepts and skills that require extensive movements within a 3D environment. Finally, around 10% of the studies (shown in Table 1 and Fig. 11) were focused on the evaluation of usability and immersion with no measurement of learning or training goals.

Advancing with this analysis, some conclusions on VR-SG experiences and their impact on training and education can be outlined. Nevertheless, the marked differences between the target audiences and the fields of application of the papers that were surveyed complicate any statistical conclusions on those issues. Regarding their educational impact, most research works pointed (in order of importance) to: 1) the main advantage of these solutions for communicating visually acquired knowledge; 2) greater student motivation when working in a VR-environment rather than in a traditional one; and, 3) the synergies with traditional teaching methodologies, focusing each methodology on different learning topics (*e.g.* traditional teaching can be used to empower the relationship between different concepts presented in VR-environments with extensive discussions between students moderated by the teacher).

Regarding the impact on training, most studies have (in order of importance) pointed out that: 1) VR-SG solutions have a very interesting cost-effective relation (highly accurate learning, low learning times, high visualization and understanding…); 2) the immediate transfer of behavioral skills in VR-environments to the real world; and, 3) the potential to heighten learning skills in a risk-free environment. Finally, research from both fields has outlined that the impact on training is often measured among final users whose experience of VR-environments and interfaces is very limited. They expect that the impact of VR-SGs will be much higher in the short-term, as those devices permeate daily life and the final users will become familiar with them before any learning/training experiences. The same argument (low user familiarity with VR devices and interfaces) was also mentioned in the studies with negative results for VR-SG solutions as a possible explanation for their poor performance.

Future research lines

Different future research lines have been proposed in the articles included in the two surveys: some directly in the present Section and some identified in the discussion of the “Results” Section. Besides, the analysis of the surveys, presented in Sections 3 and 4, raises some open questions.

One of the most demanding improvements proposed in the survey is the use of robust evaluation methods that will increase confidence in the results. This comment has already appeared in the first reviews on Virtual Reality applied to teaching ten years ago [98]. In many cases, the studies used no reference group at all, because they drew no comparison between the performance of their VR-SGs and other learning methodologies. However, most of the study cases with a reference group tested the VR-SGs in target and reference groups of very limited size. Therefore, the enlargement of the size of both groups would be advisable in the future to achieve conclusions with a degree of statistical significance. This lack of comparison or the limited size of testing groups is also mentioned in similar reviews on the analysis of the educational use of video games [44], SGs for learning software project management [24], and spatial games for Cultural Heritage topics [90]. Besides, most studies used only one of the following evaluation procedures: questionnaires, user interviews, data recording, and direct user observation. A combination of two of these procedures, especially questionnaires and indicators extracted from data recording, would also increase confidence in the results, especially if standardized questionnaires were created. This strategy would increase the validity and reliability of the conclusions, as others authors have pointed out [115]. The definition of new indicators that are directly connected to learning rates is necessary, in relation to the indicators taken from recorded data. Up until the present, the proposed indicators have only shown a solid relation with the proposed performance of the task in medical applications, while the SG score is the only indicator considered in the educational applications.

Besides, although four different key factors (learning rate, skill improvement, immersion and usability) were identified in this review, only one key factor was measured in the studies under analysis. The development of study cases that evaluate up to three of them would be of great interest, combining learning improvements, immersion and usability. In this way, it will be possible to reach new conclusions on the correlation between the design parameters of the VR-SGs and the learning goals, as other authors have outlined for similar tasks, such as spatial games for cultural heritage [90] and ball-based sports improvement [99]. Besides, design strategies of VR-SGs may be identified in this way. For instance, VR-SGs have some way to go, before they reach an optimal level of use for teaching very abstract concepts and training skills that require complex movements in a 3D environment. Along those lines, comparative studies of VR-SG efficiency are needed between final users with extensive experience of video-gaming and users whose interests are unrelated to such games.

The two surveys raised some open questions on the best design strategies of the VR-SGs for different learning objectives and final applications. First, are VR-SGs equally efficient at presenting learning tasks and at skills improvement? In those reviews, the VR-SG applications are balanced between skills improvement and knowledge acquisition, although there was no clear evidence that VR-SGs were equally effective at both tasks; a conclusion that arises from the balanced structure of both surveys. Second, has the best design of VR-SGs already been identified for each type of final application? Very few VR-SGs have been designed for skills improvement in education and for knowledge acquisition in industrial tasks (like industry, sports or medicine). In other words, there are very few applications in some fields where VRSGs might be very effective, but where these applications are not so immediate or expected. Therefore, an effort of imagination and open-thinking will be required to find the best design of VR-SGs in many final applications. Third, should the VR-SGs be embedded in a much lengthier learning process? Nowadays VR-SGs are presented as isolated learning experiences, where previously acquired knowledge can be applied to new problems, exercised in new contexts, thereby motivating students to seek further information. However, no correlation with other learning methodologies exists, nor is there a broader learning process and the main roles to play in this scenario.

There are also strong budget limitations on the VR-SGs analyzed in this study. Up until now, user satisfaction with these experiences has been high, certainly due in part to their novelty. In the near future, the development of a broad offer of VR-commercial games will mean more demanding end-users towards final VR-SG quality. Therefore, the development of low-cost high-visual quality methodologies for the design of VR-environments will be a clear requirement. Along the same lines, VR-SGs based on explorative interaction experiences have, up until the present, been very rare, due to their higher costs. Nevertheless, those experiences might provide higher learning rates than other VR-SG typologies and their use has a strong growth potential that should be studied.

Budget limitations have other consequence for the development of VR-SGs: VRexperiences tend to be very short and short exposure times to knowledge clearly limits the learning rate [124]. Short viewing times were expected in the past, due in part to the immaturity of HMD technology that caused VR sickness syndrome [20]. But those problems now appear to have been resolved with the new generation of HMDs and new strategies for user interaction with the VR-environment [29]. Besides, if longer VRexperiences are developed, the learning time can be considered a key factor and effective time ranges for different learning tasks can be done. However, lengthier VR-SG experiences will depend on two new requirements: 1) a multidisciplinary team with specific skill sets, unlike most of the academic research groups working on these issues; and, 2) the development of rich storytelling VR-SGs with a clear orientation towards the final objective of the learning experience. The absence of oriented storytelling is especially clear in the 10% of studies that concluded that VR provided no improvements, although no clear learning objective was identified in those VR-SGs. The same weakness was also mentioned in the context of spatial games for the teaching of Cultural Heritage [90].

Finally, Fig. 13 presents a visual summary of the main characteristics of immersive VR-SGs and their application collected in the survey for both education and training tasks. Each of the largest circles is split into four quarters, one for each characteristic of the VR-SGs: target audience, type of game, type of evaluation, and key factors to consider. The surface of each smaller circle is proportional to the number of papers included in each category. The color coding is as follows: red refers to the most common solution nowadays, grey to secondary solutions, and yellow is used for the solutions that appear to be the most promising in the near future.

In the field of education, the majority of the target audience are students, especially university students, perhaps because VR-SGs are easily accessible through university research groups. Interactive experiences evaluated by means of questionnaires, through which

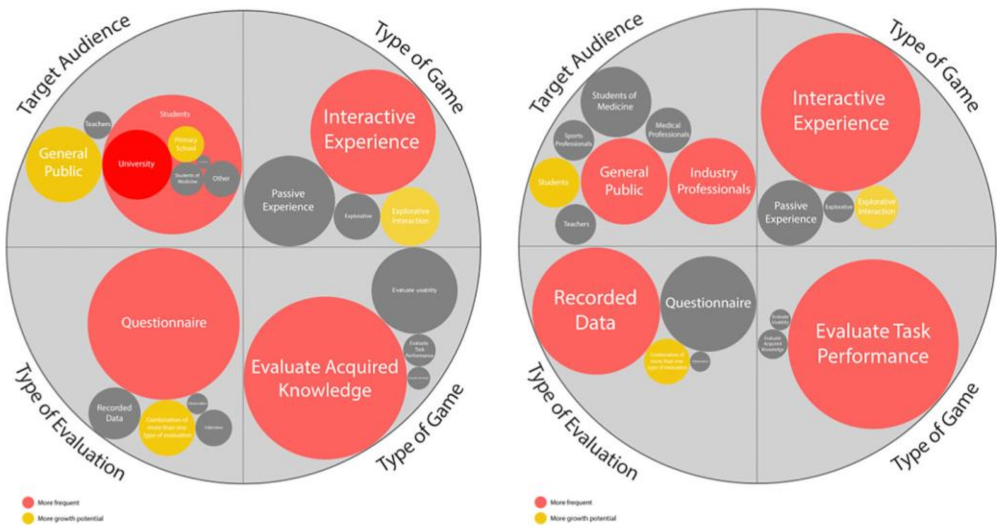

FIGURE 13: PRESENT AND FUTURE OF IMMERSIVE VR-SGS

knowledge acquisition can be ranked, are perhaps the most balanced means of assessment. However, the development of immersive VR-SGs in the near future will be very different, once they enter into mass production and become affordable products; significant growth is expected for primary school applications and general applications for the public. VR-SGs will be explorative-interactive experiences, due to their greater effectiveness in relation to different audiences and the evaluation will include additional key factors, especially immersion, using various evaluation procedures: from questionnaires to recorded data on personal performance throughout the experience.

With regard to training courses, most target audiences are industrial workers, perhaps due to the high budgets in this sector for training new employees and the imperative need for risk prevention in the workplace. In this field, the interactive experience evaluated by means of recorded data, where skills improvement can be measured, appears to be the most balanced solution. But, significant growth of applications for both students and teachers is likely in the near future; VR-SG will become an explorative-interactive experience and the evaluation will include more key factors, especially complex skills performance and immersion, using different evaluation procedures: from questionnaires to recorded data.

Conclusions

Immersive Virtual Reality Serious Games, if they are not already, will soon be capable of changing the way we perform many learning and training tasks. The technology and therefore the potential of both presence and immersion to boost VR learning processes is advancing at a rapid pace. Nevertheless, a lot of research work remains to be done, before these changes may be introduced at all stages of a learning procedure: from design strategies to the evaluation of key factors. In this review, 86 articles on VR-SGs for education or training have been analyzed. Thousands of papers that might appear to be related to immersive VR-SGs are stored on the main scientific databases. However, the limited size of the sample is because most papers, neither refer to non-immersive solutions, such as 2D virtual reality worlds, nor include a performance evaluation of the VR-environment with final users. Evaluation therefore remains a critical issue to assure reasonable conclusions related to learning rates. The survey analysis has resulted in the following conclusions:

- The launch of new high-quality affordable hardware and software media for VR has, since 2015, boosted the number of publications on these topics. A progressive short-term increase in such publications can still be expected. Although there is a lack of well-established publication forums for VR-SGs, there is a preference for training applications to be published in journals, while educational applications are mainly presented in conferences.
- VR-SG applications that involve learning and knowledge dissemination have, up until now, been considered for educational purposes, while the applications for industry and sports are still restricted to skills training. Some niches for VR-SGs to be used for training at educational institutions have been identified, such as sensitivity to bullying and motivating presentations for teachers. Medicine seems to be a very mature sector and both kinds of applications (skills improvement and knowledge acquisition) have been developed for hospital staff. Finally, important work remains to be done in the sports and industry sectors to prepare educational VR-SGs of interest that will assist professionals in acquiring the knowledge that they will require.

- Oculus Rift was preferred as an HMD rather than HTC Vive, especially in education, perhaps because of its lower price and easier configuration. On the other hand, HTC Vive was slightly preferred for training, certainly because of its better capabilities in video games of the explorative interaction type.
- Unity 3D was the preferred game engine, perhaps due to its reliable documentation and easy implementation with HMDs. Use of Unreal Engine in training applications, although in a minority, was of slightly greater significance. One reason might be that Unreal Engine renders more realistic virtual environments than Unity 3D, a key factor for certain VR-SGs that are applied to training.
- The interactive experience is the preferred VR-SG for training and education, due to its balance between costs, nowadays-technological development, immersion feeling and the possibilities that users have of learning and improving their skills. Explorative experiences might be more suitable for research tasks. Finally, passive experiences, although very economic, are very limited and rarely achieve significant learning and skill improvements.
- Two key factors were usually considered: user satisfaction and an indicator related to the objective of the experience (whether learning rate or skills improvement). Only rarely were other key factors such as immersion and usability considered. Key factors directly related to the user experience should be considered, to assure the success of the VR-experience, and their correlation with the learning rates should be measured.
- Explorative and explorative interaction VR-experiences were only developed for CAVEs and high-quality HMDs, because of the higher computational capabilities of the workstations that control these devices. In contrast, passive experiences were clearly connected to the use of cardboards, because of their technological limitations.
- Four different types of evaluation systems were found in the survey, although only two played a main role: questionnaires and recorded data. Questionnaires were the most common solution to evaluate knowledge acquisition in educational applications. In training applications, the use of questionnaires was balanced by metrics from the recorded data that were directly related to the user experience. Only very rarely were two types of evaluation procedures used in the same evaluation process.
- The target audience was usually of a very limited size, due to the high cost of the hardware compared with the more-conventional teaching solutions. The reference group, if one existed at all, had the same limitation; a fact that limited the emergence of rigorous conclusions from those studies.
- A common conclusion in all the articles that were surveyed was the higher user satisfaction with the VR-SG experience than with other learning methodologies. This conclusion was used to justify higher learning rates or

skills improvement with VR-SGs rather than with traditional learning and training methodologies.

- Only 30% of the studies really demonstrated that VR-SGs enhanced learning and training in their respective domains, while no clear advantage was observed in 10% of the studies with regard to the use of VR-SGs compared with conventional methodologies. This result shows that VR-SGs are still a very open research topic for learning and training.
- Nowadays, most of the final users enjoy the experience, but are not sufficiently familiar with the interfaces to benefit from the full potential for learning and training. The design of VR-SGs should therefore include an extensive pre-training stage, in which students gain sufficient skills through their interaction with the VR-environment.

The proposed lines of future research lead us to suggest that immersive VR-SGs will measure many key factors of a different nature within large user groups compared with a significant reference group. These experiences will belong to the explorative interaction experiences category and will be systematically integrated in standard learning programs. Finally, some of the most promising VR-SGs will belong to certain fields of application where potential effectiveness is high, even though they are not frequently employed nowadays.

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Result 2: Advantages and limits of virtual reality in learning processes: Briviesca in the fifteenth century

The development of an iVR experience and its evaluation are presented in this journal paper, in an assessment of the possibilities and limitations of Immersive Virtual Reality Environments for teaching purposes, especially in topics related to cultural heritage. The aim of this research is firstly to design an effective iVR learning experience with the intention of helping students achieve the intended learning outcomes. Secondly, it identifies and determines whether the developed iVR experience is more effective than a conventional teaching procedure such as viewing the same content on video followed by a brief discussion with the students supported by a PowerPoint presentation. This study is aligned with Objectives 2 and 3 of this Thesis. First, a practical approach is presented, with the development of an iVR learning experience applying well-defined learning theories such as the constructivist approach, the technological perspective of 3D Virtual Learning Environments and Dale's Cone theory. Secondly, an evaluative approach is deployed, conducting an evidence-based analysis of the iVR experience with a total of 100 undergraduate students.

Title: Advantages and limits of virtual reality in learning processes: Briviesca in the fifteenth century
Authors: Checa, David; Bustillo, Andres
Type: Journal
Published in: Virtual Reality, 24: 151–161 (JCR: Q1, SJR: Q1)
Year: 2020
Keywords: Virtual reality, Learning, Immersive environments, Active learning, Presence, Game engine, Cultural heritage, Oculus Rift,
DOI: https://doi.org/10.1007/s10055-019-00389-7

Abstract

Two teaching methodologies are presented and compared in this study: on the one hand, semi-guided tours in immersive virtual reality and, on the other, viewing video renderings of 3D environments. The two techniques are contrasted through 3D modeling of a fifteenth-century Spanish town called Briviesca, in an immersive environment, viewed with Oculus Rift. The suitability of virtual reality for teaching is assessed through questions on historical knowledge and urban layout. The understanding of the undergraduate students is evaluated, through questionnaires, after the viewing sessions. The responses of the students underline the effectiveness of the two methodologies: Video screenings received higher scores for historical ideas and the virtual tour was the most effective method at conveying knowledge learnt

while viewing. Additionally, two user movements for controlling the virtual reality environment were tested: (1) gamepad locomotion and (2) roomscale movements combined with teleporting. The clear advantage of the second option was the total lack of motion sickness effects. However, the natural tendency using teleporting was to move very quickly through the city areas with no singular buildings and to spend more time in front of these types of buildings. They therefore missed visual information related to the first areas while retaining more information related to those buildings. Finally, the spatial location of singular buildings was clearly better acquired with the virtual tour.

Result 3: Immersive virtual-reality computer-assembly serious game to enhance autonomous learning

In the following journal paper, both the development of an educational experience and its assessment are presented to evaluate both the possibilities and the limitations of iVR in learning concepts associated with computer hardware assembly. The aim of this research is firstly to design an effective iVR learning experience with the intention of helping students to achieve the intended learning outcomes. Secondly, it identifies and determines whether the developed iVR experience is more effective than other learning methodologies adapted to online learning like a conventional online class or using the same experience, but on a desktop PC. This study is in line with objectives 2 and 3 of this thesis. First, the practical approach is based on the development of an iVR learning experience by applying well-defined learning theories and a custom-designed model: the operational learning model. The contexts and activities in the iVR learning experience are in this model intended to promote the construction of new knowledge. Thus, students learn through autonomous interaction in hands-on learning through problem solving exercises. Secondly, an evaluative approach is deployed, conducting an evidence-based analysis of the iVR experience with a total of 77 undergraduate students.

Title: Immersive virtual-reality computer-assembly serious game to enhance autonomous learning
Authors: Checa, David; Miguel-Alonso, Ines; Bustillo, Andres
Type: Journal
Published in: Virtual Reality (JCR: Q1, SJR: Q1)
Year: 2020
Keywords: Virtual Reality, Educational Game, e-learning, Active learning, Computer Science, Game Engine, Head mounted display
DOI: https://doi.org/10.1007/s10055-021-00607-1

Abstract

Immersive Virtual Reality (VR) environments create a very strong sense of presence and immersion. Nowadays, especially when student isolation and online autonomous learning is required, such sensations can provide higher satisfaction and learning rates than conventional teaching. However, up until the present, learning outcomes with VR tools have yet to prove their advantageous aspects over conventional teaching. The project presents a VR serious game for teaching concepts associated with computer hardware assembly. These concepts are often included in any undergraduate's introduction to Computer Science. The learning outcomes are evaluated using a pre-test of previous knowledge, a satisfaction/usability test, and a post-test on knowledge acquisition, structured with questions on different knowledge areas. The results of the VR serious game are compared with another two learning methodologies adapted to online learning: 1) an on-line conventional lecture; and, 2) playing the same serious game on a desktop PC. An extensive sample of students (n=77) was formed for this purpose. The results showed the strong potential of VR serious games to improve student well-being during spells of confinement, due to higher learning satisfaction. Besides, ease of usability and the use of in-game tutorials are directly related with game-user satisfaction and performance. The main novelty of this research is related to academic performance. Although a very limited effect was noted for learning theoretical knowledge with the VR application in comparison with the other methodologies, this effect was significantly improved through visual knowledge, understanding and making connections between different concepts. It can therefore be concluded that the proposed VR serious game has the potential to increase student learning and therefore student satisfaction, by imparting a deeper understanding of the subject matter to students.

Introduction

Virtual reality (VR) technologies used within different fields have recently been successfully integrated into education, teaching and training. While VR is not new, recent advances in its technology have improved interaction and lowered costs, making it increasingly attractive to scholars. The new standalone generation of VR Head Mounted Displays (HMDs) dispenses with the inconvenience of cables that limit freedom of movement. On the one hand, almost all published studies of VR applications and educational goals report a clear increase in user satisfaction compared with conventional teaching methodologies. But on the other hand, those studies fail to prove a measurable increase in learning rates when using VR applications (Checa & Bustillo, 2020a). A tangible advantage in favour of immersive virtual reality as a reliable pedagogical tool over less interactive and conventional teaching approaches must be shown in terms of learning performance, in order to achieve universal recognition for immersive VR.

In the general context of the COVID-19 pandemic, undergraduate students have had little choice other than to face high levels of confinement and have seen their social life curtailed, including social interaction during their learning process. On-line learning has become a major tool in their daily life, drastically reducing one of the main positive outcomes of the learning process: the emotional component of learning. Clearly, new technologies cannot provide this emotional component; however, VR might reduce its impact in student demotivation by means of increasing student satisfaction with the learning experience. The immersive sensations and feeling of presence associated with interactive VR experiences (Bhattacharjee et al., 2018) are a useful means of mitigating student isolation and the negative effects of demotivation. VR supported lectures open new opportunities of learning by doing, countering those negative effects, motivating students through practice-oriented learning content, often a preference among students.

When selecting the teaching goal for this research -computer hardware and its assembly- the central issue was student demotivation associated with non-practical contents. Computer hardware is a compulsory topic in many computer science degrees that is often presented to students from a very theoretical perspective, due to budgetary limitations. In this approach, student interaction with computer components is curtailed. Computer hardware assembly is one of the first topics to be taught in any introduction to computer science, so student interest in the topic can often be weaker, as they wish to move on to other more practical aspects. This loss of interest will affect the rate at which they learn other concepts that will be presented later on, such as programming and network security.

In this research, three different teaching methodologies are compared: a conventional teaching method, a serious game for desktop PC, and an immersive VR serious game. All of them were adapted both for con-fined and non-confined students. Therefore, its conclusions will be useful both for COVID-19 conditions and for standard life, considering that future educational standards will always insist on a major proportion of on-line learning time for undergraduate studies, in all likelihood higher than before 2019. Besides, special effort has been made to increase the sample size, so as to search for statistically significant differences between student learning rates depending on the teaching methodology. Sample size is one of the main differences with previous works, where small samples of between 16 (Zhou et al., 2018) and 27 (Ajay Karthic B. Gopinath Bharathi & Conrad S. Tucker, 2015) were selected for the experimental group. Therefore, this sample size of VR participants (n=40) is to the best of the authors' knowledge one of the most extensive for learning tasks in a homogenous population (Checa & Bustillo, 2020a).

Finally, the development of immersive VR serious games is still neither an easy nor a straightforward task. Usually, game developers and teachers who use games in their lectures are not within the same work teams. Therefore, teachers are limited to the use of existing games (Jensen & Konradsen, 2018), limiting their capabilities of optimizing the learning experience. The skillset needed to develop VR environments is still very limited, despite the release of affordable VR creation suites. In view of these limitations, the two objectives of this research are to develop an immersive VR serious game associated with computer hardware concepts that can accentuate learning outcomes and to make it accessible to undergraduate students. At the same time, the entire virtual environment and their interfaces were also adapted to a second version of the game for desktop PCs. The game comprised three stages: 1) a tutorial helps the student to get used to the VR interfaces; 2) a second tutorial helps the student to learn the main concepts of computer hardware assembly where some predefined steps must be followed; and, 3) the student completes the autonomous assembly of a computer with some pre-defined features, where the student has full freedom to interact with different hardware in a virtual lab.

The objectives and novelty of this research refer to VR learning outcomes, while keeping in mind the role that the serious game design plays in these outcomes. Up until the present, the learning capabilities of VR serious games have mainly been harnessed for training students to accomplish tasks; final evaluations in-volving repetition of those tasks. In this research, however, the academic accomplishments of the students will involve recalling outcomes, understanding skills and visual recognition of components not presented in the same form during the VR experience. In this way, our research is focused on the capabilities of VR serious games to generate new knowledge for the student. The higher cognitive load of VR learning experiences compared with 2D experiences and conventional teaching methodologies may be expected to enable a deeper understanding of the subject matter under study. The added-value of a comparison between 3 different learning methodologies in an extensive group of students is to assure the significance of the extract-ed conclusions. At the same time, the importance of a properly designed VR serious game is pondered in this research, so that high levels of student satisfaction and game usability are assured, as well as gaming applications not only in VR environments, but also in 2D screens for a broader use, especially in case of student confinement.

The remaining sections of this paper will be organized as follows: in Section 2, the most recent works on immersive virtual-reality serious games to enhance autonomous learning will be presented. In Section 3, the development of the immersive VR serious game for computer hardware learning will be described. In Section 4, the evaluation process and the learning experience performance will be described, after which the results of the learning experiences will be presented in Section 5. In Section 6, a detailed comparison will be presented between these results and recent related works. Finally, the conclusions and future lines of work will be presented in Section 7.

Related work

The teaching goal of identifying and assembling computer hardware components that is proposed in this research could be considered as a mere assembly task. Some previous studies have proposed VR serious games as suitable tools for learning by building devices. Ajay Karthic et al. (2015) focused their research on teaching procedural skills and information. They compared VR devices with desktop solutions for learning how to perform a product functional analysis; the analysis task consisted of assembling the components of a coffee maker. Their study concluded that the performance outcomes (assembly time) using immersive VR systems was significantly better than using non-immersive VR systems. This result cannot be directly ex-tended to other VR experiences, because the study had some limitations: it used a standard joystick inter-face (a low usability device compared with new interfaces) and the 54 students showed a broad age range (10 years) and a strong gender imbalance (13% female). Zhou et al. (2018) used an educational computer-assembly application to explore the influence of virtual reality on user game experience. They concluded that the use of VR heightened learning interest and fostered engagement, although any analysis of learning rates associated with different teaching methodologies was not approached. Finally, Zhou et al. (2018) concluded that students using VR took the same time to perform an assembly task as other students who had no previous practice with real components, while Koumaditis et al. (2020) reached the opposite conclusion. They concluded that study groups of twice the size (33 users compared with 16 people in the case of Zhou et al.) performed complex mechanical tasks (*e.g.,* assembly of a 3D cube) in reality with greater efficiency in statistical terms than in VR environments. Therefore, many questions remain open concerning the effect of VR educational applications on learning rates and the influence of VR interface usability on learning out-comes, which may be partially resolved with larger sample sizes.

Computer hardware, it may be remarked, might not be the best topic to teach through immersive VR learning experiences. Any other topic with a closer relation with spatial elements may be more suitable and provide better learning scores when using VR, due to higher spatial visualization in VR environments (Molina-Carmona et al., 2018). Most of these topics may belong to Medicine (Moro et al., 2017), Mechanical Engineering (Wolfartsberger, 2019), Architecture (Kowalski et al., 2020) and Cultural Heritage (Checa & Bustillo, 2020b). However, the use of VR tools for computer science learning (Pirker et al., 2020) is not new in itself. Most of these studies identify important advantages when VR devices are used. Akbulut et al. (2018) found students who had a VR experience based on the concepts of software engineering scored higher than students who did not undergo VR learning. The use of analogies and metaphors to build mental models can benefit from the use of virtual reality, as experiences that teach theoretical concepts have shown such as finite state machines and object-oriented programming (Dengel, 2019; Tanielu et al., 2019). The findings of other research (Greenwald et al., 2018), which compared VR fundaments of science learning with desktop-based VR and 2D images, showed no clear advantage of VR-based instruction. Considering Bloom taxon-omy (Bloom, 1956), some of these studies reported basic learning objectives, like remember, to describe educational goals; for instance, remember firewall filtering rules (Puttawong et al., 2017). Other studies focus on understanding concepts, such as finite state machines (Dengel, 2019) or fundamental programming principles [Horst]. Finally, some approaches focus on higher cognitive levels, such as creation in the sense of inventiveness (Bujdoso et al., 2017). As a further step in researching, this work tackles not only one of these categories but a combination of them, in order to achieve further educational goals. Secondly, former works focus on student´s capability to remember specific tasks, previously trained in VR environment. Contrarily, this research targets the potential of serious VR games to help students acquire new knowledge not directly provided in the same form; in other words, the student´s skill to generalise knowledge from specific examples. Therefore, visual recognition of a limited set of physical elements plays a secondary role in this research as opposed to other literature, in which the success of learning outcomes is assessed in terms of tasks trained by using the same set of physical elements. Finally, previous works did not compare the learning outcomes provided by different teaching methodologies. In most of them, VR is the only tested teaching methodology (Bujdoso et al., 2017; Dengel, 2019; Puttawong et al., 2017). Only in a few cases, like (Horst et al., 2019), VR is compared with other methods, like desktop serious games, but traditional learning methodologies are never used for baseline comparison. To overcome this limitation, this research tests three different teaching methodologies to identify their advantages and drawbacks when acquiring different types of knowledge.

Development of an immersive virtual reality serious game

The VR-serious game used in this research was designed following a previously presented design methodology (Checa & Bustillo, 2020a). This methodology is composed of three stages: pre-design, game development and game evaluation. In the pre-design, a clear and testable learning hypothesis or objective is de-fined. The hypothesis is based on mainstream modern learning theories. During the game development, game and instructional features are developed while programming the serious game in the game engine. Game features should promote motivation to learn, while minimizing the entertainment impact (extraneous processing). Instructional features should increase the instructional impact (essential processing) without reducing the motivation (generative processing) as Mayer and Johnson stated (Mayer & Johnson, 2010). Finally, student performance with the serious game is evaluated in a third stage, by measuring whether there has been an improvement in the learning outcomes. A learning outcome is a change in knowledge caused by instruction. The evaluation is divided into two issues: 1) measurement of student satisfaction; and 2) measurement of learning outcomes. Student satisfaction includes the evaluation of satisfaction, usability and simulation sickness, which was assessed at the end of VR experience.

Pre-design

Following this methodology, the first step was to develop a clear and testable hypothesis. The subject "Introduction to Computer Science" is a mandatory study unit on all the engineering degrees and others, such as the Degree in Media Communication, taught at the University of Burgos (Spain). In addition, this subject is particularly complex to overcome for many students, due to the diversity and abstract nature of its contents. One of the first learning topics in this subject is computer hardware assembly, a topic that includes knowledge of computer components and their functionality, performance units, range of variation depending on the final use of the computer, etc. These concepts are currently supported by presentations that include computer images, data tables and diagrams. Unfortunately, practical exercises with these contents might require sufficient computers for each student to have one to disassemble, to extract components and to replace them, which are not always available due to cost constraints. In this research, the aim is to create an educational game that prompts students to interact with these concepts, so that they are learnt in a practical way. Moreover, the game should be an attractive and dynamic tool for students, that introduces them to the subject with positive learning results, providing additional motivation to work towards better grades on the course.

Three well-defined learning theories and one custom-designed model were followed to design the serious game as a suitable educational resource. Learning theories can be defined as proposals related to the way students assimilate, process and retain the information they have learnt, and provide guidelines on students' motivations, learning process and learning outcomes (Pritchard, 2017). First, the theory of Liu et al. (2017) identified constructivism, autonomous learning, and cognitive load theory as the most suitable issues for VR serious games. Secondly, the technological perspective of the 3D Virtual Learning Environments (Dalgarno & Lee, 2010) was also taken into account. This theory focuses on representational and interactive fidelity; the learning benefits in this theory are split into: representations of spatial knowledge, experiential learning, engagement, contextual learning and collaborative learning. Thirdly, Dale's Cone theory (Dale, 1946) can also be suitable for VR serious games. According to this theory, students learn best when they go through a real experience or the experience is realistically simulated. Finally, our research follows the operational learning model proposed by Zhou et al. (2018) that proposes a learning model in which aspects of Human-Computer Interaction and pedagogical aspects are merged, considering logical contexts, roles and scenarios of VR environments. This model uses constructivism at the abstract level, because the contexts, activities and social interactions in the learning environment promote the construction of new knowledge. Students therefore learn through autonomous interaction, hands-on learning, and problem solving. VR technologies offer 1) realistic experiences in which to practice these principles, 2) a safe environment where mistakes can be corrected, and 3) immediate feedback provided on operational learning.

Game Development

Roussos et al. (1999) defined four key objectives for the design of a VR serious game: interaction, immersion, user participation and, to a lesser extent, photorealism. The accomplishment of all these objectives is possible with new game engines and HMD devices. They present very high resolution, wider field of view, ultra-precise tracking and 6DOF interaction elements, creating a very strong sense of presence and immersion. The steps followed to develop the VR serious game are summarized in Figure 1. They include: 1) 3D model creation, 2) integration of these models in the game engine, 3) development of the 3D virtual environments, 4) creation of the VR learning experience, and 5) adaptations for VR and desktop applications.

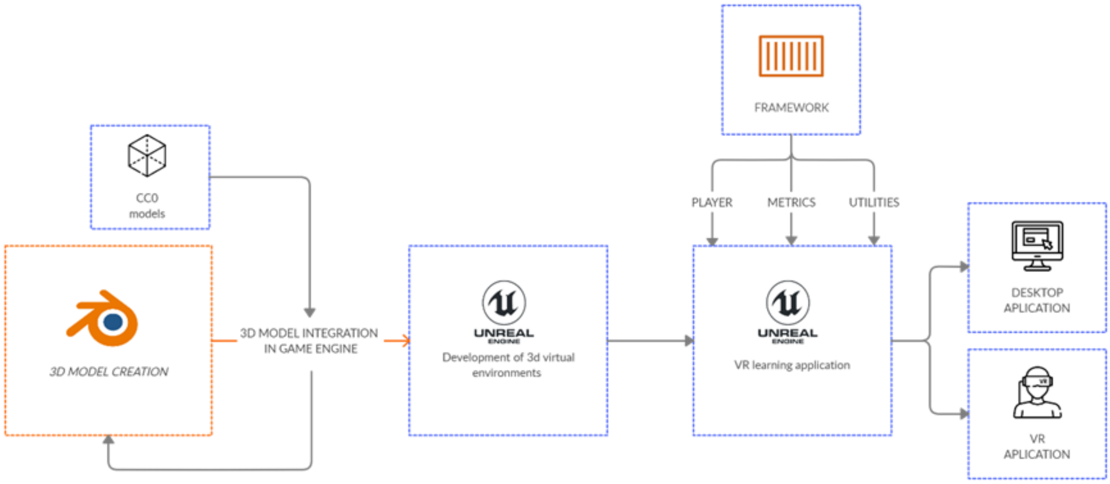

FIGURE 6: PIPELINE OF GAME DEVELOPMENT

Blender software was applied to create the 3D models. Besides, some 3D models, released under CCO licenses, were also downloaded from different sources. These models were integrated in the game engine. Unreal Engine™ was chosen, due to its high capacity to create photorealistic environments and its visual scripting system, blueprints that are used to create very complex experiences with little or no knowledge of programming languages, as former works have demonstrated (Checa et al., 2020; Checa & Bustillo, 2019). 32 unique PC hardware objects were modelled and categorized in 8 different sections: CPU, CPU Cooler, GPU, Hard Drives, Mainboards, RAM, power supply, and PC Cages. Only one class and one corridor were modelled for the environment. Figure 2 shows some examples of the 3D models and the virtual environment.

Figure 2: Examples of the 3D models and the virtual environments included in the serious game.

When creating VR learning applications, the first step is to choose the type of VR experience properly. VR learning applications can be divided in four types: Explorative Interaction, Explorative, Interactive Experience, and Passive Experience. In Explorative Interactions, the user explores the environment and interacts with it freely. In contrast, an explorative experience simply involves free exploration, although without direct interaction. The Interactive Experiences permits user interaction, but no free movement. Finally, the Passive Experience is the most limited one, in which user interactivity and movement are very constrained. Most VR learning applications use passive experiences, because they are more easily created with low-cost solutions. However, although student satisfaction is improved, significant learning improvements are not achieved (Checa & Bustillo, 2020a). Therefore, Interactive VR Experiences are currently the most appropriate type, because they show a good balance between cost, current technology development, immersion, and interactivity. This solution is more cost-effective than Explorative Experiences and is therefore the type of serious game selected in this research.

The VR serious game was developed with the support of a previously created framework (Checa et al., 2020). The framework simplifies the game development process with functions and services that are pre-programmed for their effective reuse such as player utilities, an evaluation manager, and tools for metrics. This framework also makes it possible to have a single project that can be played on a 2D screen or on VR devices, merely by changing the pawn that automatically detects whether or not the user has connected a compatible VR device. On the one hand, if the user plays on a 2D screen, the interface will be the mouse and the keyboard, on the other hand, if a VR device is used, the interaction will be through hand controllers. The game works with Oculus Touch controllers, used in this study, but it is also compatible with HTC Vive and Windows Mixed Reality headsets and controllers. Game design decisions were oriented to achieve natural interactions as well as to mitigate any usability constraints of the controllers. The game design was focused on usability, with a limited interaction technique in VR, to accelerate the learning curve of the user: among the 3 basic forms of interaction techniques in VR (selection, manipulation and locomotion) the user only had to focus on the manipulation of objects. A single mechanism was used to pick up and to drop objects as well as to place them in position. The user had to press and to hold the controller trigger to pick up objects and the hand dropped the objects when the button was released. An attachment system was programmed to help the user to place the object in the desired position when it was sufficiently close to the attachment point, to facilitate the assembly task of the computer. The outline of the hand was also high-lighted in a light green colour whenever within range of an object, to facilitate grabbing. The objects floated back to their original locations a few seconds after being released, to prevent users from accidentally drop-ping or throwing parts away. This design solution avoided the use of a specific button-based mechanism, that could be difficult for a novice user. Finally, a first level ensured that the implementation of the interaction could not interfere with its performance where users might become accustomed to this method of inter-action.

If played on 2D screens, the interaction in the game is controlled with a keyboard and a mouse, using the left click to pick up, to drop and to place objects. The movements use the arrows or AWSD of the keyboard. Figure 3 shows a user interacting with the game with a VR device and the same action in a desktop version.

Figure 3: User interaction with the mouse and keyboard in the desktop game (left); controller interaction in the VR game (right).

As Figure 4 shows, the VR experience was designed so that students could progress through different levels and advance towards the following goals:

- Introduction: At this level, the user follows a semi-guided tutorial to learn how to use the VR inter-face as well as the mechanics, such as grabbing and placing objects, that will be used in the game later on. The novelty of the VR environments and interfaces can limit the user's learning experience, especially if they have never used those devices before or are unfamiliar with them. Known as the "novelty effect" or Hawthorne effect, this issue refers to the way the virtual information on display and the technology may distract students (Looi et al., 2009). The introduction that has no time limit is an attempt to circumvent the novelty effect, giving the user sufficient time to become familiar with the technology and interfaces.

- Tutorial: the student, guided by the virtual instructor, has the task of assembling a computer. The tutorial is a fixed step-by-step process where students receive continuous feedback and help from the assistant robot (spot 1 in Figure 4.A) to learn where each component should be placed. This assistant only displays information when the student looks directly at it, helping to avoid visual over-load of the space, which could adversely affect student attention levels. The student has to slot the different computer components into place according to the design (spot 2 in Figure 4.A). The board, situated in front of the assembly table, serves as a reminder of the academic content, showing the main information on the component that the student is positioning in real time (spot 3 in Figure 4.A). This step also serves to circumvent the novelty effect and initial astonishment at the VR environment that can reduce the attention levels of students when focusing on the learning experience in the next step. It also helps students to become familiar with the information and the way it is presented, thereby mitigating, in the final assignment, the distraction of the virtual information on display.
- Assignment: through self-instruction, the student has the task of assembling a computer, which in-volves the selection of mutually compatible components, their proper positioning, and their connection in a reasonable order. There is a wide variety of hardware from which to choose, although the PC to be built must meet certain requirements (spot 5 Figure 4.B). The student can check the specifications of each component, in order to perform this task successfully, placing the component in an information location on the assembly table (spot 4 in Figure 4.B). In this way, the student will be able to choose the right component and can proceed to assemble the hardware in the cage (spot 6 in Figure 4.B). The required specifications of the computer are shown to the left of the whiteboard, while on the right-hand side the user can see the specifications of the computer once it has been assembled and can check whether the right components have been used.

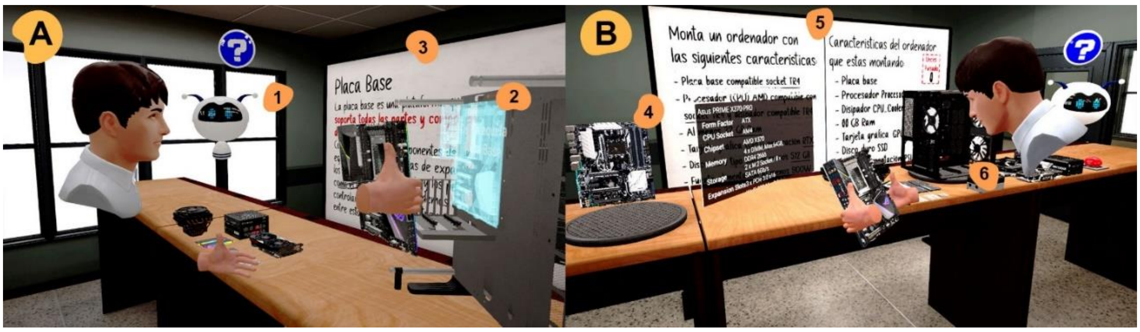

Figure 4: A: tutorial level (left) A1: assistant robot, A2: test bench where the user places the different computer elements, A3: Board showing the main information of

the grabbed component. B: assignment level (right). B4: information location that shows relevant characteristics of the hardware, B5: board with the requested requirements, B6: variety of hardware and cage in which to place it

This experience has been created for both desktop (2D screens) and immersive virtual reality versions. The desktop version works with any computer with medium processing requirements and has been optimized to run at over 90 fps on an IntelR CoreTM i5-8600 processor, minimum 8GB RAM and NVIDIA GTX 1050. Immersive virtual reality version has more hardware requirements and has been optimized to work properly on computers with at least 16GB RAM and NVIDIA GTX 1070 graphic cards. Both versions of the serious game can be downloaded from the following URL https://3dubu.es/en/virtual-reality-computer-assembly-serious-game/. Besides, this webpage includes several videos of students playing the serious game in virtual reality and on desktop PCs that provide a broader vision of the performance of the game.

Finally, as the game experience was to be compared with a conventional lecture, a lecture experience was also designed. In this lecture, the teacher presents the computer hardware components in detail, using an open computer to interact with the hardware, while the student is unable to manipulate the components. In this lecture experience, the teacher followed the same steps for assembly as were in the game, considering hardware limitations (no extraction of screwed components). The students' role was limited to viewing the teacher's actions, through a webcam broadcast, and listening to the explanations. Although, the students were sitting in the classroom and a beamer was projecting the webcam broadcast, the broadcast could just as easily have been followed through web services in case of student confinement. The event was baptized the webcam experience, as a webcam was used to display teacher interaction with the computer.

Learning experiences and evaluation process

Following Mayer's proposal of teaching experience design (Mayer, 2014), any teaching experience should be compared with valid, reliable, objective and referenced instruments with experimental control groups that use conventional modes of teaching. In this research, the VR serious game was compared with two conventional teaching methodologies. First, the same game was used with one control group but playing in desk-top PCs. This group will benefit from some of the advantages of a serious game: autonomous learning, hands-on motivation and problem solving. However, this group also has some limitations: the mouse and the keyboard are used as the game interface, which is a slightly less natural interface, and users miss the benefits of immersion and presence associated with VR environments. The second control group enjoys a learning experience based on an instruction class that explains the main components inside a computer by displaying its different parts in great detail through a webcam that projects the images on a large screen. The computer has most of its components disassembled and during the class students watch as many components are assembled: the CPU dissipator, RAM, hard drives, power supply, and graphics card. The duration of this class was 25 minutes, which is very close to the average time that the other groups spent playing the game.

The study was conducted as part of the Introduction to Computer Science subject in the Media Communication degree of the University of Burgos. The study sample consisted of 77 first-year students (mean age = 18.6 years old, 37 male and 40 female). The participants were randomly assigned to three different groups: Virtual Reality group (40 students), Desktop PC group (19 students) and Webcam Experience group (18 students). All relevant dimensions of both the treatment and the control groups were equivalent (Mayer, 2014), while the Virtual Reality group was larger, because is the one under study and a higher variability is expected. Although the two control groups (Desktop and Webcam groups) initially had 20 students, some students were omitted, because they had missed some of the lectures or they had not filled in the tests. The size of each group was defined by taking into account the following design factors: 1) number of learning methodologies to be compared; 2) the homogeneity of the groups of students; 3) higher expected performance variability in the VR experience, due to its novelty; 4) the statistical techniques (ANOVA and ANCOVA) for the results analysis, 5) the limited effect of the learning experiences on academic outputs, due to their short duration, and 6) a minimum of 15 students in the reference group. These criteria are properly derived from the existing bibliography (Birckhead et al., 2019; Gall et al., 2003). Then, the availability of students and their separation into practical groups were considered to fix the final size of each group for each learning methodology.

The learning experience includes four stages: previous test, master class, learning experience itself, satisfaction questionnaire and, finally, a knowledge test. Figure 5 summarizes the workflow of this process. All the students received identical treatment, except for the type of experience they performed (VR, desktop PC or webcam-based experience).

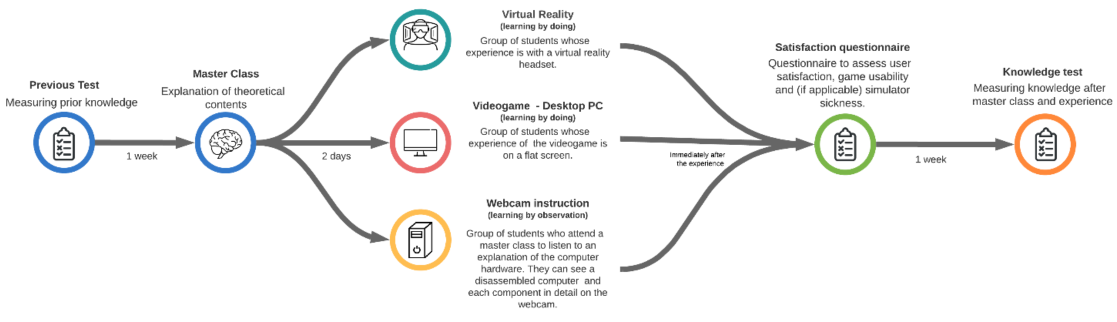

Figure 5. Design of the whole learning experience including evaluation stages.

The learning experience began with a pre-test to assess the previous knowledge of students. It consisted of 9 Multiple Choice Questions (MCQ) and one image-based question to identify the different components of a computer viewed without one of its side panels. The pre-test took place before the students had received any lecture on computer hardware and can be consulted in the Appendix I. Although we can find conflicting positions on the advantages and disadvantages of using MCQ, in general it has been considered more ap-propriate to test large amounts of surface knowledge throughout a study unit (Excell, 2000). A week later, the theoretical contents that constituted this didactic unit on computer hardware were explained in the form of a master class with the learning objectives “Recalling” and “Understanding”. Two days later each group carried out the corresponding learning experience: playing the serious game in VR or the same game on a desktop PC or giving group presentations in class to explain the internal positions of computer components while observing webcam images of its parts. Immediately after the experience the students from the first two groups filled in a questionnaire to assess user satisfaction with the experience, game usability, and simulator sickness. The usability questionnaire was adapted from (Tcha-Tokey et al., 2016). The learning objectives that are associated with the serious game are “Understand” and “Create”. The surveys administered to each group can be consulted in Appendix II.

Finally, a week after the experience, a knowledge test was performed. The test was not completed immediately after the experience, because delayed tests are particularly useful when determining the persistence of learning outcome effects (Mayer, 2014). If administered immediately after the experience, much of the in-formation may still be stored in the short-term memory, so the test results might not reflect comprehensive learning or long-term retention. The test included different questions from the pre-test, because equal tests can affect the learning evaluation. A pre-test can also serve as a learning episode (Johnson and Mayer, 2009), and if the same test is used as post-test, it can often lead to better marks than questions drawing from the learning experience. The post-test contains 21 questions: 15 multiple-choice type questions, 4 open questions, the answers to which are a chance to demonstrate conceptual knowledge through extended explanations and that probe student understanding of the educational content. Finally, the last 2 questions refer to PC images in which users have to write the name of each component in an empty blank. The test was designed to respond to a multi-level assessment by focusing on retention (recalling essential information), transfer (capability of using the learning information to solve new problems and to adapt to new situations) and understanding. The questions were divided into two categories on the basis of Bloom’s taxonomy (Bloom et al. 1956). The first group (7 questions) were related to recalling or remembering information. The second group of 6 questions referred to the understanding of information, in particular from class discussions, and conceptual knowledge. In addition, the two image-based questions served to identify, locate and recognize different components of a computer. The higher learning objectives associated with the post-test were "Apply" and "Analyze" and they can be consulted in Appendix III. The operational learning model used in this research is summarized in Figure 6.

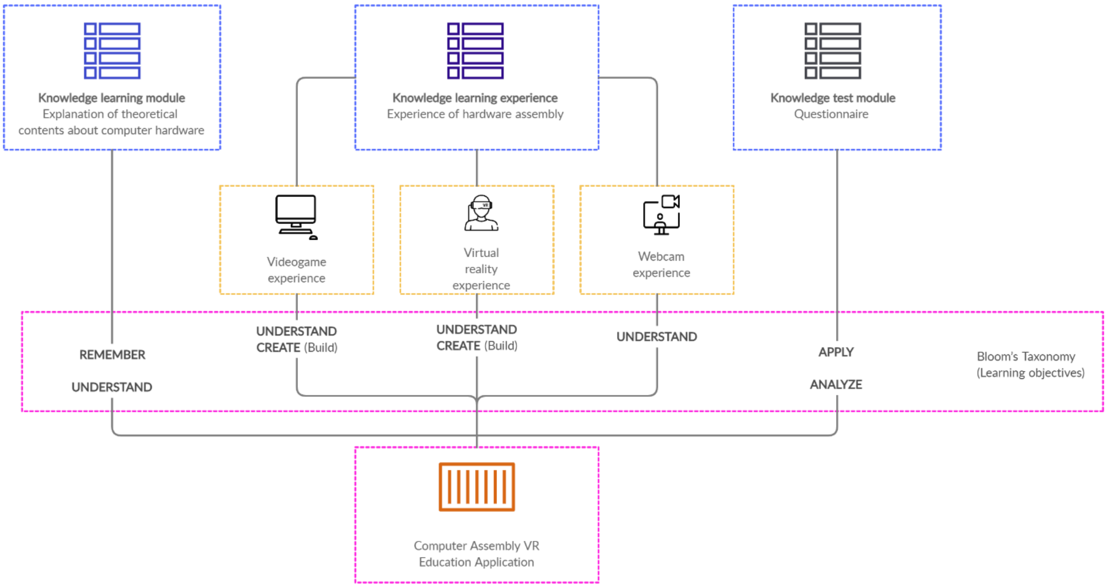

Figure 6. Operational learning model used based on the proposed learning model in (Zhou et al., 2018).

The procedure followed in the learning experiences changed with each group. The VR group used Oculus Rift HMD and Oculus Touch controllers. Five stations were set up with computers equipped with IntelR CoreTM i7-4790 CPU 3.60 GHz, 16GB RAM, with NVIDIA GTX 1070 graphic cards. The procedure followed the recommendations for the prevention of COVID-19 transmission. Several consecutive days were necessary for these preventive measures, so that all students could take part in the experience. The Desktop group used the computers equipped with an IntelR CoreTM i5-8600 processor, 8GB RAM and NVIDIA GTX 1050 available in the regular classroom. Finally, for the webcam experience group, we used the normal classroom with the help of the projector connected to a webcam. Figure 7 shows the 3 learning experiences as they took place.

Results of the learning experience

In this section, the results obtained with the different evaluation tests and the other performance indicators will be collected. The raw data and their analysis presented in this section can be found in Appendix IV. The data were analyzed at $\alpha = 0.05$ using the XLSTAT Statistical Software version 2018 (Addinsoft, New York, NY, USA) and are presented in terms of their Mean (M) values and Standard Deviation (SD). Welch's statis-tical tests were applied in the analysis to check for any possible sample imbalance.

Satisfaction with the experience

All the groups were administered a short survey to measure student satisfaction with the educational experience, immediately after the experience. The first survey questions were on their satisfaction with the experience (0-very low to 5-very satisfied) and then on their learning belief concerning the learning experience and its suitability for acquiring the required knowledge (0-not useful to 5-very useful). A one-way ANOVA based on the survey results yielded the information summarized in Table 1. A significant difference between the satisfaction of the VR group ($p < 0{,}0001$) and the Desktop group ($p = .003 < .05$) compared with the Webcam group was found. These results indicated that the use of a serious game in the learning experience in both the desktop and the VR versions produced a significant improvement in student satisfaction com-pared to the traditional teaching method. The students also gave very positive learning belief ratings to the VR ($p = .016 < .05$) and the desktop versions ($p = .036 < .05$). The higher scores of the VR versus the desk-top version of the game for both questions should also be highlighted.

Table 1: ANOVA of the satisfaction survey (M – Mean value, SD - Standard Deviations) for VR, Desktop, and Webcam groups

Variable	Type of learning	N	M	SD	P
Satisfaction	VR	40	4.34	0.85	< 0.0001**
	Desktop	19	3.83	0.70	0.003*
	Webcam	18	2.94	0.96	
Learning beliefs	VR	40	4.56	0.70	0.016*
	Desktop	19	4.27	0.75	0.036*
	Webcam	18	4.05	0.65	

*$p < 0.05$, **$p < 0.0001$

The Usability of Serious Games

Four questions on the usability of serious games were included in the satisfaction questionnaire adapted from (Tcha-Tokey et al., 2016). All of them used a five-point Likert-type scale ranging from (1) strongly disagree to (5) strongly agree. The first question asked users about how well they thought they controlled the game interface (Q3). The second asked whether the interactions seemed natural (Q6). The last 2 questions referred to the clarity of the goals and the physical configuration (Q4 and Q5). A one-way ANOVA was con-ducted, and the results, summarized in Table 2, showed that participants thought it was significantly more natural to interact in VR with Oculus Touch than on the desktop with the mouse and the keyboard. Previous investigations have arrived at similar results (De Paolis & De Luca, n.d.) that might explain the result of Q3, where the VR users were able to control the game slightly better than the desktop users. Finally, although the VR group understood the information displayed in the game, they expressed a more intense impression that they had been partially lost in at least one step of the game. These feelings may respond to a precarious game design at certain steps that should be remedied in future experiences.

Table 2: ANOVA of usability survey (M – Mean value, SD - Standard Deviations) for VR, Desktop, and Webcam groups.

Variable	Type of learning	N	M	SD	P
Q3: Have you been able to control the game without problems?	VR	40	3.48	0.86	0.215
	Desktop	19	3.16	0.98	
Q4: At each step, did you know what to do?	VR	40	3.29	1.14	0.773
	Desktop	19	3.38	1.24	
Q5: Is the information provided within the game clear?	VR	40	4.51	0.55	0.421
	Desktop	19	4.38	0.50	
Q6: Did the interaction with the virtual environment seem natural?	VR	40	4.24	0.79	0.015*
	Desktop	19	3.66	0.84	

*$p < 0.05$

Performance in game

Some conclusions on user performance time at each stage of the game can be advanced. In Table 3, the ANOVA analysis is summarized. The time spent by the VR group was significantly longer at the introductory level. This level was used to enhance user familiarity with the environment and its physical configuration. In the second phase, a guided tutorial on PC assembly, the VR group was a bit faster than the Desktop group. Finally, in the Assignment phase, the VR group was significantly faster, finishing the proposed task more quickly. Besides, the game records the number of errors made in the Assignment phase. The VR group had an average of 2.1 errors per user while the Desktop group reached 2.8. So, the VR group was faster and more precise for computer assembly. A relationship can be established between the higher usability of the VR version with the Assignment time. In addition, although VR users were not familiar with the VR interface, they could clearly compensate that lack of confidence with an extra minute of training (Introduction level).

Table 3: ANOVA of performance times (M – Mean value, SD - Standard Deviations) for VR and Desktop groups.

Variable	Type of learning	N	M (in minutes)	SD	P
Time in Introduction	VR	40	4.36	0.76	< 0.0001**
	Desktop	19	3.11	0.69	
Time in Tutorial	VR	40	3.70	1.00	0.058
	Desktop	19	4.29	1.15	
Time in Assignment	VR	40	12.95	4.73	0.017*
	Desktop	19	16.52	5.70	
Total time	VR	40	21.17	5.45	0.087

	Desktop	19	24.05	6.40	

$*p < 0.05$, $**p < 0,0001$

Academic achievement

The pre-test included 10 questions that evaluated previous knowledge of computer hardware. A right answer was recorded as 1 and false ones as 0 and the responses to the 10 questions were averaged. Table 4 shows the average values and the one-way ANOVA. The low marks indicated that the students possessed insufficient computer-hardware-related knowledge before the learning experience, especially in the VR group. The non-significant effect between groups is required for a later comparison between group performance (Mayer, 2014).

Table 4: ANOVA of the averaged Pre-test questions for VR, Desktop, and Webcam groups.

Variable	Type of learning	N	M	SD	P
Pre-test scores	VR	40	0.48	0.20	0.32
	Desktop	19	0.53	0.25	0.91
	Webcam	18	0.54	0.25	

The post-test included 21 questions. A right answer was recorded as 1, and if otherwise as 0. The analysis of the differences between the three groups was conducted with an Analysis of Covariance (ANCOVA) using the pre-test scores as the covariate and the post-test scores as dependent variables. Table 5 summarizes the ANCOVA results, in which the mean values of the post-test scores were 0.54, 0.50, and 0.47 for the VR, the Desktop and the Webcam group, respectively. Between the VR and Webcam groups a significant difference was found ($p = .003 < .05$), indicating that VR students showed significantly better academic performance than the group that received the traditional lecture. The Desktop group also showed slightly better marks than the Webcam group, but at some distance from the positive results of the VR group.

Table 5: ANCOVA of the post-test (M – Mean value, SD - Standard Deviations) for VR, Desktop, and Webcam groups.

Variable	Type of learning	N	M	SD	P
Post-test scores	VR	40	0.54	0.19	0.03*
	Desktop	19	0.50	0.17	0.62
	Webcam	18	0.47	0.19	

$*p < 0.05$

The graph plotted in Figure 8 reflects an evaluation of this result, not only from averaged values but also from a general picture of each student's performance. It shows (Y-axis) the improvement percentage for each student normalized to its averaged mark in the pre-test ((post-test – pre-test)/pre-test). On the X-axis, the pre-test average mark is plotted. An examination of Figure 8 shows higher improvements (Y-values) in all ranges of pre-knowledge (X-axis) among the VR users. The students with very low marks in the pre-test especially showed higher improvements, which was a very interesting result that reflects the potential of VR for student learning of new though difficult hardware topics, opening up new avenues for future research with specific interventions with these sorts of students.

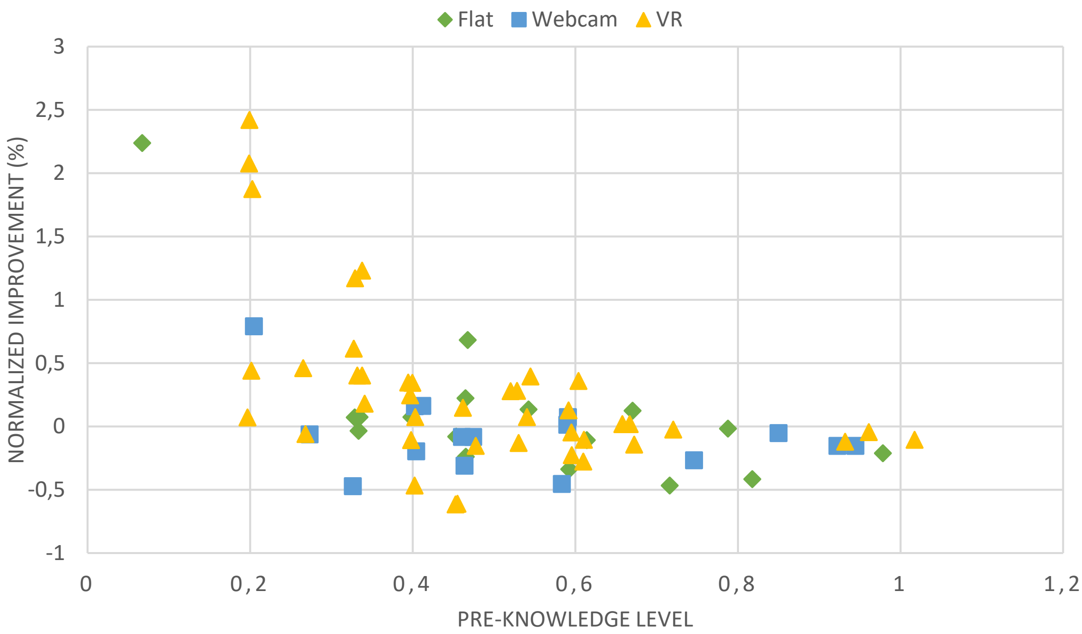

Figure 8. Normalized improvement in terms of participants prior knowledge

As stated before, the post-test questions were divided into different categories. The first group was related to recalling the information of the pre-test questions. The second group concerned the understanding of information and discussion. Finally, the third group was a set of image-based questions. A separate analysis was therefore performed for the 3 groups of questions, for an in-depth analysis of the results of the post-test.

Information recall

The questions forming this section (7 in the pre-test and 7 in the post-test) were focused on student ability to recall or remember essential information. The one-way ANOVA showed no significant effect between groups in the pre-test. An ANCOVA analysis was therefore performed using the pre-test scores as the co-variate and the post-test scores as dependent variables, Table 6. Neither were significant differences found between groups. The Webcam group achieved the best averaged results, while the roughly equivalent results of the VR and the Desktop groups were slightly worse.

Table 6: Analysis of the answers of the VR, the Desktop, and the Webcam group to questions on information recall.

Variable	Type of learning	N	M	SD	P
ANOVA analysis of answers to the questions on recalling information in the Pre-Test: Q2, Q3, Q4, Q5, Q6, Q7, Q8	VR	40	0.58	0.20	0.297
	Desktop	19	0.62	0.17	0.163
	Webcam	18	0.51	0.28	
ANCOVA analysis of answers to questions on recalling information in Post-Test: Q1, Q2, Q4, Q9, Q13, Q14, Q15	VR	40	0.52	0.20	0.304
	Desktop	19	0.51	0.26	0.201
	Webcam	18	0.55	0.26	

A final analysis of this group of questions was focused on the only two questions that were repeated be-tween the pre-test and the post-test (Q3 and Q5). Those questions were the most complex, because less than half of the users answered them correctly in the pre-test (42% for Q3 and 41% for Q5). In both, 76% and 60% of the students answered those questions correctly in the post-test without any statistically significant difference between the three methodologies.

Understanding

This group of 6 questions was intended to measure the understanding of the information and, in particular, to give the possibility of discussing and demonstrating conceptual knowledge to the students. The one-way ANOVA showed an almost significant effect between groups in the post-test, between the VR and the Desk-top groups and a slight better result than the Webcam group, Table 7.

Table 7: ANCOVA analysis of the answers of the VR, the Desktop, and the Webcam groups to questions on understanding in the post-test.

Variable	Type of learning	N	M	SD	P
Answers to questions on understanding in the Post-Test questions	VR	40	0.50	0.22	0.05*
Q6, Q8, Q10, Q17, Q18, Q19	Webcam	18	0.42	0.19	0.64
	Desktop	19	0.37	0.23	

Within this category of questions, it is interesting to analyze the only question repeated from the pre-test: How long (in minutes) do you think it takes to mount two RAM modules and the graphics card in a computer? (Q17). The correct time was set at around 10 minutes. The one-way ANOVA, Table 8, showed no significant effect between groups in the pre-test. The ANCOVA analysis of covariance showed significant differ-ences ($p = .003 < .05$) between the VR and the Webcam groups, highlighting the good performance of the VR group. Besides, the VR group was the one that came closest to 10 minutes and improved most with respect to the pre-test.

Table 8: Analysis of the answers of the VR, the Desktop, and the Webcam groups to Q17 from the post-test questions.

Variable	Type of learning	N	M	SD	P
ANOVA analysis of the responses in the Pre-Test to the question on the time (in minutes) that it takes to mount the RAM and the graphics card of a computer	VR	40	22.8	19.25	0.20
	Desktop	19	13.17	10.82	0.49
	Webcam	18	16.68	17.11	
ANCOVA analysis of responses in the Post-Test to the question on the time (in minutes) that it takes to mount the RAM and the graphics card of a computer	VR	40	9.78	6.54	0.003*
	Desktop	19	14	12.18	0.170
	Webcam	18	17.35	10.91	

*$p < 0.05$

Visual recognition

Finally, the category Visual recognition was based on assessing the capability of students to recognize and to locate computer hardware components. For this purpose, 6 questions were asked that addressed visual aspects of the hardware. Only one question was repeated between the two tests (Q10 in the pre-test and Q20 in the post-test), although its difficulty was slightly greater in the post-test. As Figure 9 shows, in the pre-test, Q10 asks the user to select the right name of each component from a list, while in the post-test, Q20, the user only has a blank space on each component, and the proper name of the component should be recalled and written down. Besides, the computer images shown in the questionnaires are not exactly the same as the computer cage displayed in the serious game, as shown also in Figure 9. The one-way ANOVA showed no significant effect between the groups in the pre-test. The ANCOVA analysis showed significant differences ($p = .021 < .05$), indicating that the VR group achieved significantly better visual recognition than the Webcam group, Table 9.

Table 9: Analysis of the answers of the VR, the Desktop, and the Webcam groups to the visual recognition questions.

Variable	Type of learning	N	M	SD	P
ANOVA analysis of the answers to the Visual recognition questions in Pre-Test questions	VR	40	0.39	0.26	0.17
Q9, Q10	Desktop	19	0.39	0.28	0.23
	Webcam	18	0.50	0.31	
ANCOVA analysis of the Visual recognition questions in Post-Test questions	VR	40	0.55	0.25	0.021*
Q5, Q7, Q11, Q12, Q20, Q21	Desktop	19	0.53	0.28	0.098
	Webcam	18	0.44	0.27	

*$p < 0.05$

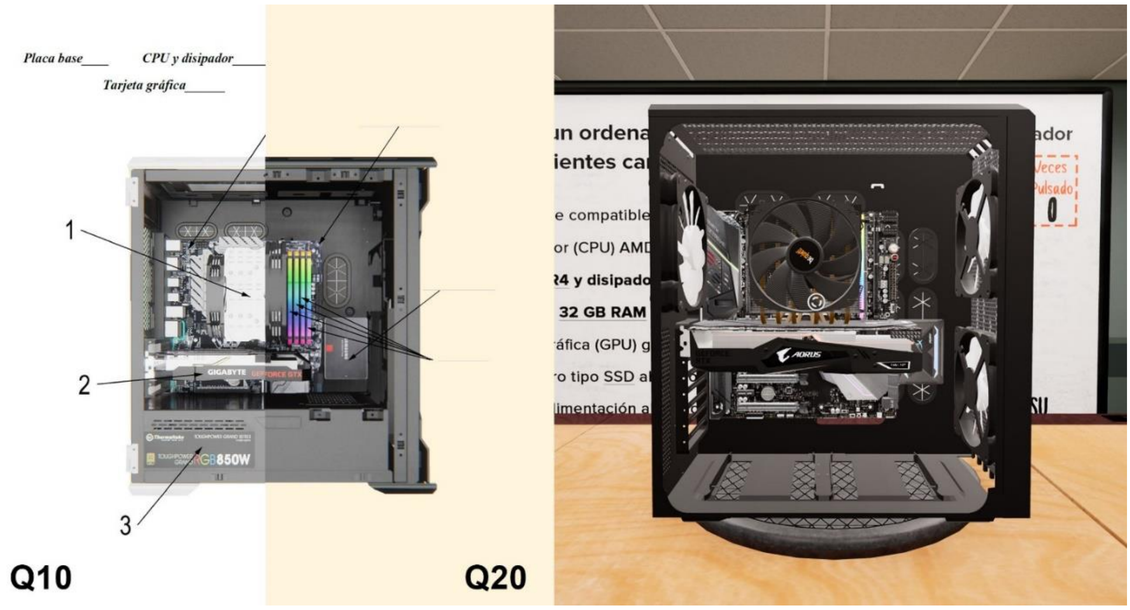

Figure 9. Q10 (pre-test) and Q20 (post-test (left) and computer cage in the serious game (right)

Discussion

Firstly, the analysis of the results revealed significantly more satisfaction among the students who per-formed the VR experience, while the Desktop group reported less satisfaction although still far better than the control (Webcam) group. Although the higher satisfaction with the VR experience might come from the novelty effect of the VR environments, this effect hardly appears to be the only reason, because the Desktop game also achieved high satisfaction levels, which may partially be due to the hands-on learning strategy of the serious game compared with conventional learning methodologies, as pointed out in previous works (Makransky et al., 2019). Besides, this difference between the VR and the Desktop groups could be linked to the different interfaces, showing the VR controllers and the higher feeling of natural manipulation of the physical configuration in comparison with keyboard and mouse controls, as both objective and subjective indicators show. This effect has previously been reported in some general studies: usability plays a major role in student satisfaction reports (Chen et al., 2013) and some with similar learning tasks (Zhou et al., 2018), as is also proposed in this research. It was observed that the VR participants spent more time on the Adaptation level, but they were faster than the Desktop group in the Assignment level. This first result on higher satisfaction with VR was expected; it is a common conclusion in VR studies compared with conventional teaching methodologies (Checa & Bustillo, 2020a): young students perceive VR within education as an exciting and challenging opportunity once a minimum of expertise in the VR interface is gained. Gaining greater expertise is highly recommended to provide VR users with more time to explore and to adapt to the learning environment, in order to minimize the "novelty effect" of this technology.

In the bibliography, the higher satisfaction with VR methodologies is commonly connected with higher learning rates, although these conclusions are, in most cases, never statistically evaluated with a proper sample of users (Checa & Bustillo, 2020a). The analysis of the tests on academic performance showed a significant difference in the learning rates for the serious games users in opposition to the control (Webcam) group, for both the VR and the desktop game versions. This improvement suggests that serious games are a suitable tool for enhancing learning. Likewise, the VR game showed better results than the desktop game, which suggests that the increased learning in the VR condition was not a direct result of the game, as it was the same in both cases. Instead, the learning appears to be attributable to both 3D immersion and the interactivity of the VR environment, as recent research has outlined (Buttussi & Chittaro, 2017).

However, not all kinds of knowledge are especially suitable for VR games. Figure 10 illustrates the results obtained with the different satisfaction surveys and the evaluation tests of the educational experience, showing the averaged mark (1: maximum satisfaction/acquisition rate) of each group for the four considered outputs. The results revealed different learning stages as defined in Bloom's taxonomy: for example, the slightly worse results for information recall from the serious games groups in comparison with the traditional learning group. This aspect has been mentioned in the literature (Checa & Bustillo, 2020b) and is based on the cognitive theory of multimedia learning, which predicts that students will learn more with a well-designed slide presentation, even though they may report lower levels of interest and motivation (Parong & Mayer, 2018). Although there were very poor improvements at recalling information with VR, the final analysis of the most complex questions for this kind of knowledge shown in Section 5 showed a clear improvement for those questions from the pre to the post-questionnaire. The conclusion was that all the proposed teaching methodologies helped student learning processes.

On the other hand, VR and conventional conditions were more conducive to 'understanding' than the Desk-top, as some previous results have also pointed out (Allcoat & von Mühlenen, 2018). Compared to observation-based learning methodologies, the chance to interact with components can significantly enhance the acquisition of different types of knowledge (Borsci et al., 2016) among users and their performance of well-established procedures (Buttussi & Chittaro, 2017). Finally, visual recognition and knowledge is clearly better acquired in both interactive and immersive VR environments compared with traditional approaches, showing slightly better results than the Desktop group. This result was especially significant, because the proposed questions evaluated each user's ability to extrapolate the acquired knowledge to new scenarios (e.g., identifying computer components within a significantly different computer cage than the one dis-played in the serious game).

This type of evaluation is significantly different from the one used in VR training games where it is mainly the same items and procedures that usually appear in the tests (Abich et al., 2021). It appears clear that VR is of great potential for the acquisition of this kind of knowledge, as outlined in some previous studies (Checa & Bustillo, 2020b; Molina-Carmona et al., 2018).

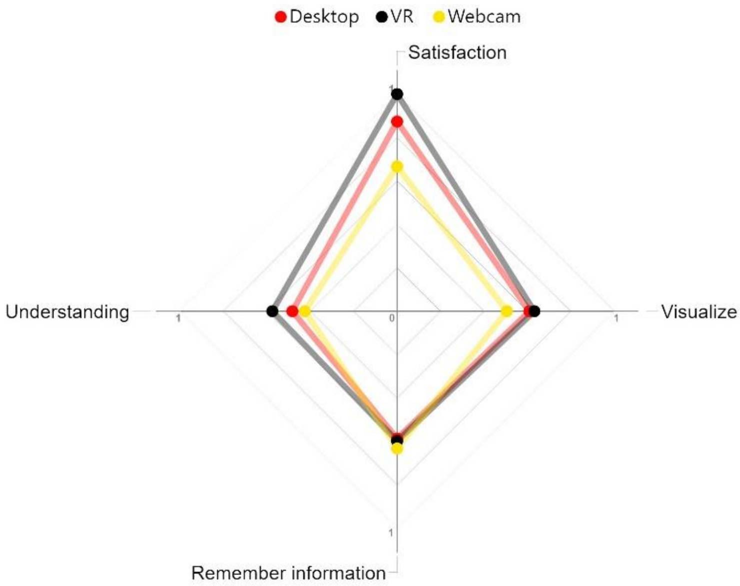

Figure 10: Effect of the three teaching methodologies in the different learning outcomes

Conclusions

Firstly, a VR serious game for teaching computer hardware assembly to undergraduate students in an introductory study unit to Computer Science has been presented in this research. The game has been designed to mitigate various obstacles detected in VR educational applications such as the "novelty effect" and user's astonishment due to the technological novelty or lack of interface control. Tutorial stages and natural game interfaces have been used for this purpose. The game is designed as a hands-on learning environment to increase interest, because students prefer practice-oriented learning content rather than memorization of facts. This design follows the idea that rather than better teaching of traditional knowledge, the real potential of VR is found in "learning by doing", which is usually very difficult to apply in traditional classes.

Secondly, the VR-serious game has been integrated in a complete learning experience and compared with another two learning methodologies. Those reference methodologies were based 1) on the same serious game, but for a desktop PC, and 2) a conventional lecture adapted to on-line learning times, where the computer hardware is presented by the teacher with a webcam and an open computer, although the student is watching and cannot manipulate any components. An extensive group of students (n=77) was selected with a major proportion (n=40) in the VR group, to evaluate the performance of these 3 learning methodologies. The analysis of a knowledge pre-test, a satisfaction/usability test, a knowledge post-test, and some performance indicators have yielded the following conclusions:

- Student satisfaction: the game in both its desktop and VR versions significantly improved student satisfaction compared with the traditional teaching method. Besides, students gave more positive learning beliefs ratings to VR ($p = .016 < .05$) than to the desktop game or conventional class meth-ods. This result is especially interesting against the backdrop of the COVID-19 crisis and student confinement, when student health and well-being should receive special support: if we enjoy learn-ing, obstacles might appear smaller.
- Game usability: the students thought it was significantly easier to interact in VR than the desktop PC version controlled by a keyboard and a mouse. Besides, they found that the VR environment was slightly easier to control than those playing the game on a desktop.
- Information recall: the slightly worse results of the serious games groups at recalling information than the traditional learning group may be highlighted.
- Understanding: on average, VR showed a slightly better performance. However, VR students per-formed significantly better that the desktop and the Webcam students in response to questions on the time that is required for RAM assembly and improved their results in comparison with the pre-test. This leads us to suggest that the sensation of immersion was better than the other two options at helping students to extract applied knowledge for real life.
- Visual recognition: students who used the VR application showed significantly better visual recognition than the group that received the traditional class and had slightly better results than the students using the desktop serious game.
- Performance: the VR group performed the exercise faster and made fewer errors than the students playing the same game on the desktop. A relationship can be established between the greater usability that users perceive of VR with the time required to complete the learning task. In addition, the fact that they spent more time at the introductory level may have meant that the VR users were more focused on the subsequent levels that are relevant for learning.

All these conclusions point to the following: 1) the strong potential of VR serious games to improve students well-being in times of isolation due to higher learning satisfaction; 2) the positive effect of learning theoretical knowledge, but specially for developing understanding and connection between different concepts; 3) although computer hardware might not be a topic that is closely connected with spatial knowledge, as with many topics such as Cultural Heritage, Mechanical Engineering and Architecture, VR still provides significant advantages compared to other methodologies for student absorption of visual knowledge; and, 4) the usability of the game and the use of tutorials are directly connected with user satisfaction and game performance.

This research has helped to answer some questions, but many others still remain open for future research. The effect of VR applications on a continuous and stable learning process should be reported as other authors have stated (Ray & Deb, 2016), because once the students feel comfortable and competent with the VR interfaces and the game design, then the learning outcomes may be boosted. For instance, the impact of the novelty effect should be quantified. Besides, not only longer experiences, but also novel learning methodologies have to be developed to assure the right overlap between conventional lectures and autonomous RV learning sessions. For instance, home VR solutions should be tested and compared with class-room high-end VR solutions as the one presented in this research. Finally, new learning topics where a high-er degree of visualization and experiential awareness is required must be tested, to establish the limits of VR in relation to learning tasks. For instance, VR solutions for dangerous-task training, like electrical hazards in industrial equipment maintenance.

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4. Conclusions

In this thesis, the advantages and limitations of Immersive Virtual Reality (iVR) educational applications in learning have been approached from three points of view: analytical, practical and evaluative. The conclusions derived from these perspectives are discussed below.

4.1 Analysis of iVR experiences from the standpoint of their learning purpose

Firstly, in Result 1, a critical review of the literature on iVR for learning purposes has been conducted for a better understanding of the possibilities and the limitations of the technology. In this review, the facts or advantages that have previously been proven and the limitations of the iVR experiences that have been published so far have all been pointed out. Besides, the barriers to the incorporation of iVR into educational programs have been identified.

iVR technologies are advancing at a rapid pace. Publications on these topics have multiplied since 2015 when the democratization of these technologies became widespread. The survey that we have conducted has shown that, despite the thousands of articles related to iVR for educational purposes found in scientific databases, most of these articles either refer to non-immersive solutions, or include no evidence-based approach to evaluation. From these experiences, it is worth highlighting the very limited size of the target audience, usually due to the high cost of hardware compared to a more conventional educational solution. The reference groups had the same limitation; according to Cohen (Cohen, 1988), if a large effect is expected, at least twenty-five participants are needed in each group and, if the expected effect is in the small range, one hundred per group. Therefore, this survey takes into account only those studies that conducted assessments that 1) specified the learning objective and 2) used reliable, objective and referenced methods with which to measure the learning outcome.

As regards iVR educational-experience design, the first conclusion is that iVR interactive experiences are mostly preferred in education, due to their balance between cost, current technological development, sense of immersion and possibilities for users to improve their learning. Secondly, some passive experiences associated with devices with no direct interaction capabilities are also included. Although these experiences are very cost-effective, they are also very limited and rarely achieve significant learning improvements. Finally, there are hardly any exploratory interaction experiences, since their development is complex and costly. For the time being, their use is mainly limited to serving as a complementary element and not as a main learning resource in the educational process, but they show promising potential for future growth.

Regarding evaluation, the first key measure is user satisfaction. A common conclusion in all the considered articles was higher user satisfaction with the iVR experience (of any type) compared to other learning methodologies. However, although they enjoy the experience, most users are not sufficiently familiar with the interfaces to take advantage of the full learning potential of iVR. The design of the experiences should therefore include an extensive pre-training phase where learners acquire sufficient skills through their interaction with the iVR environment.

The second key measure in the evaluation process is the academic learning outcome. So, designing appropriate dependent measures is crucial to provide high-quality evidence. Multilevel assessment is recommended that, at least covers retention (remembering the information) and transfer (using the learning to solve new problems). Questionnaires were the most common solution to assess knowledge acquisition. Three types of questionnaires were mainly considered: pre-test, post-test and embedded experience test. Generally, learning outcomes are measured in the form of gain between pre-test and post-test.

The results of these studies showed mixed evidence since only 30% of the studies demonstrated that iVR improved learning. While no clear advantage was observed in 10% of the studies regarding the use of iVR compared to conventional methodologies. The remaining studies achieved no statistically significant results.

However, some advantages of iVR versus traditional learning have been identified. Higher levels of student motivation and engagement are expected using iVR experiences. Also, a higher degree of interaction with the environment can boost learning. iVR experiences are effectively applied to complex, expensive and dangerous environments to learn about any related topic. These advantages should be taken into account when defining iVR experiences, to optimize student learning and satisfaction outcomes. However, much research work remains to be done before these changes can be introduced at all stages of a learning experience ranging from design strategies to the evaluation of key factors.

4.2 Design effective iVR learning experiences

Two teaching experiences, presented in Result 2 and Result 3, respectively, have been designed to test the possibilities and limitations of iVR environments for learning. These experiences were developed with the intention of helping students to achieve the learning objectives. The design of these experiences follows the previously identified key factors for successful design and use of iVR in educational contexts:

The *pre-design* phase is focused on defining the learning objectives aiming to improve learning through the introduction of iVR technologies. The learning objective must be important and enhanced by the introduction of iVR technologies. Therefore, experiences were designed to teach concepts that have proven to be resistant to conventional pedagogy. In Result 2, an experience was designed to determine the suitability of virtual reality for teaching historical knowledge and urban layout in cultural heritage related topics. In Result 3, the experience was designed to assess the students' ability to recall information, and their comprehension and visual recognition in computer science subjects. In these experiences, a significant question that can be empirically investigated was proposed: Does an iVR experience result in better academic learning than receiving the same content through conventional media? In Result 2, two teaching methodologies are presented and compared: on the one hand, an iVR experience and, on the other hand, the viewing of a video. In Result 3, the iVR experience is compared with two other learning methodologies adapted to online learning: 1) a conventional online class; and 2) using the same experience but on a desktop PC. In both experiences, a design instruction was defined to enable the effective use of virtual reality capabilities to support desired outcomes, based on existing learning theories. Three well-defined learning theories and one custom-designed model were followed in these experiences. Both iVR experiences mainly use the constructivist approach. This theory presents learning as an active process, in which learners construct knowledge on their own (rather than passively receiving information) (Duffy & Jonassen, 2013; Fosnot & Perry, 1996). The constructivist philosophy holds that learning is obtained when the student plays an active role, constructing knowledge in a learning-by-doing situation. Secondly, the technological perspective of the 3D Virtual Learning Environments (Dalgarno & Lee, 2010) was also taken into account in the design of these iVR experiences. This theory focuses on representational fidelity; the learning benefits are split into representations of spatial knowledge, experiential learning, engagement and contextual learning. Thirdly, Dale's Cone theory (Dale, 1946) was also taken into account. According to this theory, students learn best when the experience is realistically simulated. Finally, a custom-designed model was followed, found only in the Result 3: the operational learning model proposed by Zhou et al. (Zhou et al., 2018). This model uses constructivism at the abstract level, because the contexts and activities in the learning environment promote the construction of new knowledge. Students therefore learn by autonomous interaction, hands-on learning, and problem solving.

In the *design* stage, it is crucial to identify the best technologies to be used, especially the game engine to utilize and the most suitable HMD. Both experiences were designed to be viewed with Oculus Rift HMD and controlled with Oculus Touch controllers as their interaction interfaces. This HMD presents very high resolution, wider field of view, ultra-precise tracking and 6DOF interaction elements, creating a very strong sense of presence and immersion. Unreal Engine™ was chosen as our game engine, due to its high capacity to create photorealistic environments and its visual scripting system, blueprints that are used to create very complex experiences with little or no knowledge of programming languages and provides reliable support for virtual reality devices. The game design techniques applied in the development of these iVR experiences support the processes of selection, organization and integration of information. There is one identified obstacle that limits these processes: the "novelty effect". An obstacle that can be minimized using the tutorial stages and natural interfaces that have been designed. Finally, the design the iVR experiences includes other important aspects like: 1) 3D model creation, 2) integration of these models in the game engine, 3) development of the 3D virtual environments and programing the iVR learning experience inside the game engine.

4.3 Evaluate evidence-based iVR learning experiences

The study of the effectiveness of iVR was approached with the question *What works?* referring to the learning effects of using an iVR experience versus learning in a non-immersive environment. Experimental comparisons were performed such that the treatment and control groups received identical treatments except for the element being manipulated. In this case, the element manipulated in all experiments was the delivery medium: iVR or conventional media. As stated above the conventional approach was, in the first case: videos followed by a brief discussion with the students supported by a PowerPoint presentation. In the second, the baseline techniques were an online class and the use of the same experience, but on a desktop PC. Likewise, students were randomized between the control and treatment groups. A total of 100 undergraduate students participated in the first experiment and 77 in the second. Cohen (Cohen, 1988) stated that at least 25 participants are needed in groups before a large effect size may be expected. The results were analyzed using appropriate measures including means, standard deviation and sample size. The results of these experiences point to the following conclusions:

The conclusions of the analysis of these two experiences have, firstly, shown that younger students perceive iVR within education as an exciting and challenging opportunity once a minimum of expertise in the iVR interface is gained. If that expertise is to be swiftly acquired, then good usability is essential in the design of the experience. In our experience, the students thought it was significantly easier to interact in iVR than in the other less immersive mediums i.e., a desktop PC. This effect has previously been reported in some general studies and points to the major role that usability plays in student satisfaction (S. Chen et al., 2013).

Secondly, significantly higher satisfaction levels were found among students in the groups that performed iVR experiences. This result was expected because it is a common finding in iVR studies when compared to conventional teaching methodologies. However, it is especially interesting against the backdrop of the COVID-19 crisis and student isolation, when student health and well-being should receive special support: if students enjoy learning, obstacles might appear smaller. The educational experiences conducted in this thesis find that higher satisfaction with iVR methodologies is related to higher rates of learning.

Thirdly, another interesting insight obtained from the experimentation is that iVR has been found to promote different types of learning, such as "comprehension", defined by Bloom as the ability to interpret, exemplify, classify, infer, compare and explain. (LW et al., 2001). Furthermore, "Remembering", which is defined as the ability to recognize (identify) and recall (recall), related in these experiments to visual recognition, is clearly better acquired in iVR environments compared to traditional approaches.

Fourthly, not all types of knowledge will be better-learnt by means of iVR experiences. iVR shows lower effectiveness for recalling information than traditional learning approaches. This fact is demonstrated in both experiments. A probable reason may be found in the cognitive theory of multimedia learning, which predicts that students will learn more with a well-designed slide presentation, even when reporting lower levels of interest and motivation (Parong & Mayer, 2018).

All these conclusions point to the following: 1) the usability of iVR experiences is directly connected with user satisfaction and performance in the experience; 2) the positive effect of learning theoretical knowledge, but especially for developing connections and understanding between different concepts; 3) iVR provides significant advantages compared to other methodologies for student absorption of visual knowledge.

5. Future lines

This thesis has helped to answer some questions, but many others still remain open for future research. The iVR experiences presented in this thesis are just a small sample of the educational potential of immersive virtual reality in the classroom. As in the conclusions of this thesis, future lines of Immersive Virtual Reality educational applications in learning have also been approached from three points of view: analytical, practical and evaluative and are detailed below.

5.1 Future lines of IVR experiences arising from the perspective of their learning purpose

Different lines of future research have been drawn from the development of this thesis. An open research question is whether the iVR experience should be integrated in a much longer learning process. Today most of these experiences are presented as isolated learning experiences, where previously acquired knowledge is usually applied to new problems or exercised in new contexts. However, there is no continuity or broader learning process over time. This is usually due to budgetary constraints, which can often have other consequences such as iVR experiences that tend to be very short. This fact reduces learning enhancement, as short knowledge exposure times clearly limit the pace of learning (Ritterfeld et al., 2004).

An additional focus of future research could address different perspectives of the four main objectives in the study of the effectiveness of iVR: *What works?, When it works?, How it works?* and *What happens?* (Mayer, 2011). Regarding comparative learning between iVR and conventional learning methodologies, most studies use an experimental approach to *What works?,* focusing on whether people learn better from iVR experiences. However, research can be done on other questions, such as *When does it work?*, whose mission is to investigate whether certain types of people learn better from iVR experiences than from conventional learning methodologies. Research can also be conducted on *What happens?*, seeking to understand what people do when they play an iVR experience. Finally, some studies already point to *How it works?*, which is to gain insight into why learners learn better in iVR than in conventional learning methodologies. Until now, this has been done by observation, interview or through the administration of questionnaires. However, all of these methods can be greatly complemented by the acquisition of data in the iVR experience.

Data on physical states can be collected by sensors that record physiological measurements such as heart rate and blood pressure, as well as body movements in addition to more specific ones such as eye movements and brain activity. The use of these large heterogeneously acquired data sets can play an important role in improving the diverse learning needs of students and current educational practices. From the students' point of view, it will enable them to improve their learning by identifying pathways that help them to achieve their learning objectives. From the educators' point of view, educators will be able to improve the quality of instruction based on real-time data reflecting student performance, participation and engagement with the subject matter. Additionally, developers of iVR experiences will be able to improve applications based on analysis of the most used elements, student feedback and teacher comments, bringing together the level of immersion to the expected level of presence. However, the amount of data to be processed makes it unfeasible without techniques that automate the processing and analysis of such huge datasets.

In this way, machine learning can be applied to understand how the user interacts with the iVR experience, so as to react and to adapt the experience accordingly. Eye-tracking data acquisition, a functionality that is fast being adopted in the new HMDs, will play a major role in new machine learning-powered teaching capabilities built into iVR educational experiences. A major advantage of eye tracking is what is known as foveated rendering (Albert et al. 2017). With foveated rendering, only what the user looks at directly is rendered at full resolution (the same way our eyes see in real life). However, its use has raised some doubts over the privacy of our digital footprint in the future in these environments (Kröger, Lutz, and Müller 2020).

5.2 Future lines of iVR learning experiences derived from their design

Regarding the design of educational experiences, there are certain standardization problems that should be solved in the near future. Although there are several companies that manufacture HMDs, there is no standard for application development that guarantees hardware or software interoperability. Therefore, the development of educational VR applications becomes a challenge when more than one vendor is supported and the technology is still in an experimental phase. However, the future is promising and some companies, such as Oculus, have already adopted standards such as OpenXR (The Khronos Group, 2021) that facilitate the development process and the implementation of iVR learning applications in curricula.

Another area open to improvement is the creation of more complex and realistic iVR environments. It can produce an increase in presence and make the experience more believable and engaging. It is also, as already highlighted, desirable to develop longer iVR experiences. The duration of learning experiences tends to be short, due to time and money constraints, and because research teams need to be multidisciplinary with specific competencies needed to develop most educational applications. Future interventions will need to use appropriate instructional activities and material designs, to minimize cognitive load and to consider longer exposure times and repeated VR sessions to promote relevant learning.

Nowadays, iVR is mostly an individual experience and some learning skills and concepts require social interaction to learn and to practice (Kreijns et al., 2003). Collaborative educational interventions have previously been shown to be more efficient than individual task solving (Johnson & Johnson, 1999). Some references to its use with iVR are reported (Šašinka et al., 2018), but more research is needed on its drawbacks, such as improving communication with other users in iVR. Some limitations of current technology mean, for example, that user avatars show no facial expressions, making communication difficult.

5.3 Future lines of iVR learning experiences derived from evidence-based evaluations

Regarding the evaluation of iVR experiences, it is imperative to use robust evaluation methods that will increase confidence in the results. It is a problem that has been dragging on since the first reviews over ten years ago (Mikropoulos & Natsis, 2011). For the adoption of iVRLEs in academic curricula, these applications must be evaluated in terms of technical feasibility and learning outcomes (Radianti et al., 2020). In many cases, the studies used no reference group, because they did not establish any comparison between the performance of iVR experiences and other learning methodologies. However, most case studies with a reference group have been used to test the experiences on target and reference groups of very limited size. According to Cohen (Cohen, 1988), if a large effect size is to be expected, then at least twenty-five participants are needed in each group and, if the expected effect size is smaller, then one hundred will be needed per group. Therefore, enlarging the size of groups would be advisable in the future to achieve results with some degree of statistical significance (Egenfeldt-Nielsen, 2006). This limitation is also faced in the studies presented in this thesis, even when the groups are large enough to draw statistically significant conclusions or otherwise for the independent variable, they are insufficient to include more parameters such as gender and whether the student uses video games regularly, among others….

In addition, future research may include evidence-based, continuous, non-intrusive assessments integrated into iVRLEs. As the learner interacts within the iVRLE, stealth assessment serves to analyze user actions, to estimate user proficiency and thus create a model that is continuously updated (V. J. Shute et al., 2008). This information allows the iVRLE to provide relevant feedback to the learner in real time and/or to adapt the

VRLE to the needs of learners (V. Shute et al., 2017). With this and by applying machine learning techniques, iVR experiences can be designed and adapted to the student's pace of learning, assessing students in real time, which seems to point to a significant improvement in learning. If these techniques, included in the experiences presented in this Thesis, are applied together with machine learning techniques, the results can be improved, since the educational experiences will adapt to the student's pace and evaluation and feedback can be provided in real time, which seems to point to a significant improvement in learning compared to other conventional methods.

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