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Translating reality into the virtual world: a study on MR applications in the cultural heritage framework

Relatore
Prof. Simone Milani

Correlatrici
Prof.ssa Maria Teresa Musacchio
Dott.ssa Elena Camuffo

Laureanda
Carlotta Pivato
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To those who believe that "the sky's the limit" (it really is).

A Padova, arte magestica, culla di libertà.

A mamma e papà.

ABSTRACT

The use of Augmented and Virtual reality applications in a large number of fields has seen a rapid evolution in the past decades, due to the technological progress that started in the first years of the 2000s. In particular, this thesis focuses on the use of immersive technologies in the cultural heritage framework, and it aims at investigating the users' perception of these kinds of technologies.

Firstly, an overview on the historical evolution of immersive technologies will be presented, followed by an in-depth analysis on the already-existing works and applications of Augmented and Virtual reality in museums and cultural heritage sites. Lastly, a subjective-evaluation project will be presented, during which participants were asked to evaluate the quality of a set of three-dimensional virtual models related to the cultural heritage framework, and then to answer a questionnaire on the technical aspects and system usability of the whole experience.

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AEC……………………..	Architecture, Engineering, and Construction
AI…………………….	Artificial Intelligence
AR……………………	Augmented reality
ARSL………………...	Augmented reality Sign Language
ASD…………………..	Autism Spectrum Disorders
ASL…………………..	American Sign Language
AV…………………….	Augmented Virtuality
BIM…………………..	Building Information Modelling
CAVE………………...	Cave Automatic Virtual Environment
CH…………………….	Cultural heritage
DHC………………….	Digital Cultural heritage
DoF…………………..	Degrees of Freedom
DoR…………………..	Degrees of Rotation
DS……………………	Double Stimulus
FoV…………………..	Field of View
FPS…………………….	Frames Per Second
HMD………………….	Head Mounted Display
HPU…………………..	Holographic Processing Unit
HUD………………….	Head-UP Display
ICT…………………...	Information Communications Technology
IR……………………..	Infrared
IT……………………..	Immersive Technologies

IoT……………………. Internet of Things

LoD………………….. Level of Detail

MAR………………… Mobile Augmented reality

ML…………………… Machine Learning

MOS…………………. Mean Opinion Score

MR…………………... Mixed Reality

RV…………………… Reality-Virtuality

SAR………………….. Spatial Augmented reality

SS……………………. Single Stimulus

TAM…………………. Technology Acceptance Model

TR…………………… Technological readiness

UNTWO……………... United Nations Tourism World Organisation

VE…………………… Virtual Environment

VOISS……………….. Virtual reality Opportunities to Integrate Social Skills

VPL………………….. Virtual Programming Language

VR…………………… Virtual reality

WoW………………… Window on the World

XR…………………… Extended Reality

INTRODUCTION

This work analyses the application of immersive technologies, more specifically of Augmented reality (AR) and Virtual reality (VR), in the cultural heritage framework. The prominent role of technology in revolutionising many aspects of our everyday lives is indeed evident, with diverse applications in the healthcare and education systems, architecture, the retail industry, and many others. Particularly, immersive technologies have enabled new kinds of relationships between users and technology itself to be created providing more interactive and meaningful experiences. However, this technical revolution is still far from being completely accepted and understood by those who are not entirely familiar with it, as it is still raising some scepticism and concerns about its potentials and possible outcomes for humans.

This topic has been chosen as it combines the knowledge of Augmented and Virtual reality acquired in the Immersive Technologies course I attended during the second year of my master's degree, and the internship at the Bo Palace, the historical seat of the University of Padua. There, I had the chance to work in a highly stimulating cultural environment that made me increasingly more curious about the way the precious nature of cultural heritage might be enhanced and preserved by the technological evolution.

Once the macro-area of the study was defined, I needed to identify a related topic of interest, a niche in the general subject matter that could be developed in the thesis. A great amount of bibliographical material was therefore studied in order to acquire as much information as possible in this respect, as well as to understand how to practically link the two aforementioned main fields of interest. The bibliographical sources analysed were mostly in the form of research papers that dealt with the use of immersive technologies in a wide range of real-life applications. These papers also covered more practical details about the technological devices generally used, as well as the way immersive experiences were perceived by participants. On the basis of this literature review, the research unit I joined at the University of Padua conducted what turned out to be a perceptual and sociological investigation on this matter. Therefore, our aim was to investigate the satisfaction and overall experience of potential users of an immersive application that could be used in museums or in other cultural heritage sites. Through this study, we verified that Augmented or Virtual reality installations and experiences offered in museums or cultural heritage sites are useful implementations that can be appreciated by all kinds of people, without the need to have some sort of preliminary knowledge of the kind of devices used. Indeed, immersive technologies are essential means to enrich one's experience and remember the content of the visit in more detail and with growing enthusiasm.

We believed it would have been effective, for the sake of a more complete study, to give readers a general overview of the main stages of the historical evolution of immersive technologies, as well as their further applications and uses. I do strongly believe that this approach will allow for a full appreciation of this kind of technologies, which will further grow and develop in future years, and of their potential on the part of less expert readers, who are nevertheless curious on the matter.

The thesis has therefore been structured as follows:

- Chapter 1, "General overview on Mixed reality and its applications", provides an in-depth analysis of the history and the evolution of immersive technologies. Here I have collected and presented chronologically the very first AR and VR devices, starting from the 1830s with Charles Wheatstone's first stereoscope that allowed people to perceive two-dimensional images as three-dimensional objects using basic stereoscopy vision. However, these kinds of devices truly flourished, in the second half of the 20th century, with proper rudimentary technological devices that later led to the creation of the state-of-the-art visors used nowadays. What emerges from this first section is that initially the evolution of immersive technologies was strictly connected to that of the military industry in the United States and the gaming industry in Japan. Once the main historical phases have been outlined, I then proceed with a series of definitions regarding the concepts of Mixed reality, Augmented reality, Virtual reality, and Extended reality. The concept of the Reality-Virtuality continuum is also introduced here, as it is useful both to give definitions of the aforementioned concepts and to introduce the theme of the restoration cycle of museum artefacts that is later discussed in Chapter 2. This first chapter also includes a useful taxonomy of the devices employed in immersive technologies following Milgram and Kishino's pioneering study published in 1994. In addition, I have provided the reader with a short guide on the main characteristics common to most modern IT devices as illustrated by Bekele *et al.* (2017). In this regard, a detailed overview on the acquisition methods of the real environment and its objects that have to be adapted to the virtual world has been presented. The chapter ends with a section entirely dedicated to the major fields of application of immersive technologies nowadays. I only took into consideration those that prove to have the most interesting applications provided by immersive technologies. In other words, I focused on the Architecture, Engineering, and Construction (AEC) industry, where Mixed reality is employed to reduce production costs and possible delays as the use of raw materials is completely avoided. I also explored the retail industry, which sees the shopping experience completely revolutionised as it is definitely more immersive and personalised following customers' desires and needs. Mixed reality also allows for a decrease in work-related accidents, as risky working activities can be performed remotely adopting the same protocols that are adopted in the healthcare industry. Lastly, I believe it would be fitting to analyse the positive effects Mixed reality technology has on the education system: the studies taken into account all prove that, when employed, immersive technologies increase the level of attention in students, as well as their interest in specific subjects where they can have the chance to learn while having fun. Moreover, IT has proven to be essential when dealing with people with disabilities. I analysed some cases of blind people managing to "feel" famous works of art with senses other than touch through haptic technology. The chapter also describes some studies that employ immersive technologies to help people with Autism Spectrum Disorder (ASD) to enhance their social interaction skills; moreover, I will present some AR mobile applications facilitating the communication with deaf people by translating sign language into spoken words, and vice versa.

- Chapter 2, “AR and VR applications in the cultural heritage framework”, can be seen as a continuation of the previous chapter, as it still provides the reader with further information about a new field of application of immersive technologies, namely cultural heritage. In this case, However, a more in-depth analysis has been carried out: firstly, the concept of “smart tourism” is introduced, as it is strictly connected with the idea of a more immersive experience for visitors, which also pays particular attention to environmental sustainability. Smart tourism is also defined as opposite to mass tourism, which was particularly popular in the late 1990s. Alongside the idea of smart tourism, I have developed the concept of “gamification”, that is to say, the application of game-like activities in real-life contexts. As already mentioned in Chapter 1 with respect to the benefits of immersive technologies in education, here again, tourists have proven to be more enthusiastic and interested in the site they are visiting when they find themselves in a stimulating environment where they can, indeed, learn by playing. In this respect, I have dedicated part of the chapter to investigating whether this application could be perceived as appropriate to all age groups and to people with all kinds of cultural and educational backgrounds. For this reason, the concepts of Technology Acceptance Model (TAM) and Technology Readiness (TR) have been taken into analysis. In this regard, Chen and Chan’s study (2014) proves that, in order to make the immersive experience enjoyable to all visitors, it is essential that it is well integrated into the site itself. In this way, visitors have to perceive the MR experience as a necessary means to enrich their experience, something that is able to trigger new feelings in them. This chapter moves on with Saggio *et al.*'s study (2011) on the relationship between the RV Continuum that was introduced in Chapter 1 and the restoration cycle of artefacts that can be found in cultural heritage sites. Researchers state the importance of immersive technology when it comes to restoring severely damaged objects without the need for any further access on the original copy, which may inevitably increase the risk of deterioration. Thanks to the employment of 3D graphics, costs can be reduced and it is possible to apply some digital restoration strategies that will present the artefact to visitors in its original shape without altering the physical item. The aim of the last section of this chapter is to present readers with an overview of some of the most relevant real-life mixed-reality applications in cultural heritage sites around Italy and Europe. They are presented in chronological order to provide readers with a clear idea of how technological evolution has made it possible to reach increasingly effective results with respect to the level of visitors' immersiveness.

- Chapter 3, "Project: A subjective evaluation of cultural heritage 3D models in VR and AR environments", presents the main details of an experiment that has been conducted at the Department of Information Engineering (DEI) to prove the claims of this study. The project involved the subjective evaluation of a set of 3D models that represent objects that could potentially be found in museums, as well as environments where an immersive technology experience could take place. All the 3D models shown to the participants had different levels of quality that had to be evaluated during the first phase of the project. In the second stage, participants were asked to fill in an anonymous questionnaire that aimed at evaluating the immersive experience and analysing both its technical aspects (e.g., questions about the quality of the objects, as well as about the way they were integrated into the environment were asked), and the system usability. This second section of the questionnaire aimed at providing us with interesting considerations on the way different kinds of participants could have perceived the experience as a whole. What is important to note here is that two subjective evaluation tests and questionnaires were carried out: the first one was conducted using a Virtual reality device (i.e., Oculus Quest 2), the second one an AR visor (i.e., Microsoft HoloLens 1). I believe it is important to have collected data regarding both kinds of reality, as they are equally employed in museums or cultural heritage sites, and also offer more complete results with respect to what I wanted to investigate in this study. Furthermore, this chapter presents some technical details of both the VR and the AR devices used in the two experiences, and it also provides further information on the participants in the tests, the play area, and the details of each specific phase of the experiments.

- Chapter 4, "Data Analysis", presents the results of the VR and AR subjective evaluation tests, and the VR and AR final questionnaires. With respect to the first set of data, namely the evaluations of the 3D models and their decreased-quality variations, once the tests were over, they have been grouped according to the different models; in this way, it was possible to see in one single diagram per model how each level of detail had been evaluated by participants. I have dedicated to each 3D model a separate sub-section of the chapter, and necessary considerations were drawn from the figures created. Lastly, an analysis of the answers to both the final questionnaires was presented in the final section of the chapter.

The participants' answers and the general conclusions of the study will be presented in the "Conclusion" section of this thesis.

CHAPTER 1

General overview on Mixed Reality and its applications

This chapter will present an introductory overview on immersive technologies and their everyday life applications in a large number of fields.

1.1 History of the evolution of immersive technologies

The concept of immersive technologies comes from the idea of creating a synthetic environment where sensorial perceptions are completely enhanced through technological devices. As stated by Freina and Ott (2015: 2-3), “spatial immersion occurs when a player feels the simulated world is perceptually convincing, it looks authentic and real, and the player feels that he or she actually is there”. However, researchers have formulated multiple definitions over the decades, emphasising diverse perspectives on the matter. Azuma (1997: 3) provides one of the most quoted definitions of Augmented reality (conceptualised as part of the immersive technologies domain), defining it as “a system that:

- combines real and virtual content,
- provides a real-time interactive environment, and
- registers in 3D”.

Slater (2009) deals with the concept of immersive technologies mainly taking into account the great amount of sensory information perceived by the user; Lee, Chung, *et al.* (2013) define it as the mean through which the well-defined division between reality and virtuality is blurred; Kumawat, *et al.* (2020) highlight how immersive technologies manages to cover the totality of the 360° space making the objects distinguishable in any direction. Nevertheless, immersiveness is achievable through highly developed computational and digital environments that allow users to experience a scenario completely detached from their reality.

To reach a clearer understanding of how immersive technologies have allowed the innovation and development of a significant number of disciplines (education, cultural heritage, and engineering as will be discussed in the following paragraphs), it could be useful to take into consideration some of its most decisive historical phases. Kumawat, *et al.* (2020) set the earliest attempts at immersive technologies in the 1920s. However, nineteenth-century Victorians were already interested in innovating the way reality could be captured. Consequently, the first ever-created stereoscope was developed by Charles Wheatstone in the late 1830s, gaining enormous popularity among the upper-middle class. Wheatstone's stereoscope exploited the fundamentals of stereoscopic vision, which allows viewers to perceive three-dimensional objects with both eyes looking at two different two-dimensional images at the same time. This very technology has remained determining for the highly sophisticated Augmented reality (AR) devices that have determined the increasing popularity of immersive technologies in a huge variety of fields.

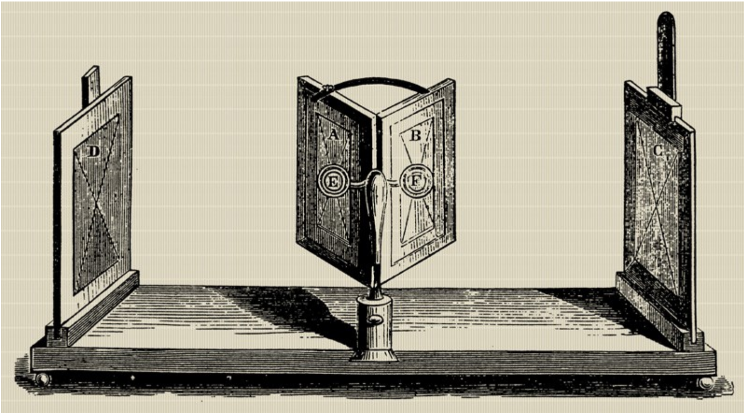


Figure 1.1: Charles Wheatstone's stereoscope, 1830. (Source: istockphoto.com)

The second half of the twentieth century is defined as decisive for the growth of this kind of technology due to the expanding and highly performing computing systems and techniques. In this new era for immersive technologies, first Morton Heilig invented the video arcade "Sensorama" in 1957 (officially patented in 1962) creating a totalising immersive experience for the film industry that involved all the senses as users could both smell and feel vibrations while watching a movie. In 1961 Philco Corp's researchers Charles Cameau and James Bryan developed "Headsight", which was used mainly for military purposes. The users' head movements were monitored using magnetic tracking and remotely mounted cameras that adapted the point of view according to the tracked head movements to create a sense of telepresence. Afterwards, Ivan Sutherland's essay "The Ultimate Display" published in 1965 managed to give the first theorised scientific vision on immersive technologies Virtual reality (VR), eventually leading to "The Sword of Damocles" in 1968. This is now regarded as the first-ever Head Mounted Display (HMD) system. The "ultimate display" in Southerland's essay title clearly refers to

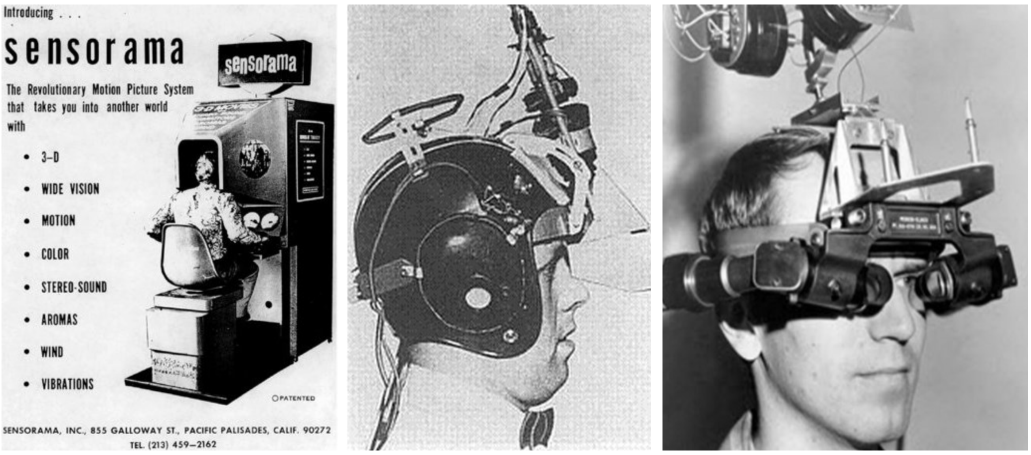


Figure 1.2: (from left to right) Morton Heilig's Sensorama, Philco Corp's Headsight, Ivan Sutherland's Sword of Damocles. (Source: Vizzari 2022)

the one that is connected to a computing device, and that can create a virtual world that can be accessed wearing the HMD and interacting with the objects displayed.

In the following decades, technological advances spawned activities (Halloway *et al.* 1991) related to immersive technologies research and advancement specifically in the US, whose government funded a great number of projects concerning Virtual reality that proved to be particularly effective for military and aeronautics purposes. For instance, between the 1980s and the 1990s, some helmet prototypes were engineered, to project information for an increasingly immersive sensory environment for pilots, which made use of motion tracking, 3D sound, and voice and gesture commands as inputs. In that same period, haptic interfaces started to be widely present both in NASA training and the nuclear industry, as they allowed remote control over a mechanical arm or vehicle. The transition towards the application of immersive technologies from merely scientific use to a wider audience developed again between the 1980s and the 1990s through the videogame industry. The high level of immersion and engagement deriving from the need to live in first person the actions of such a kind of entertainment made it possible to provide haptic devices available from VPL (Virtual Programming Languages) Research. This pioneering company was established by computer scientists Jaron Lanier and Tom Zimmerman; the former is believed to have officially coined and popularised the term “Virtual reality”. Some of the most well-known products were haptic devices such as DataGlove, the DataSuit and the EyePhone, an HMD.

In addition, in the early 1990s, major videogame companies such as Nintendo and Sega launched their first attempts at Virtual reality integration into their consoles (i.e., Sega VR headset and Nintendo’s Virtual Boy, namely what is considered to be Nintendo’s greatest market failure). At the end of the decade overall disappointment, partially due to the socially isolating and awkward game experience of the consoles and their lack of must-have games encouraged users to spend a great amount of money on them (Zachara 2009). This in turn led to a drop on the demand of the consoles, as well as a lowering investment on Virtual reality by most of the gaming companies.

Figure 1.3: Jaron Lanier's DataGlove, EyePhone, and DataSuit. (Source: gamesnote.it)

Figure 1.4: Sega VR headset, and Nintendo's Virtual Boy. (Source: ign.com)

At the beginning of the 21st century, however, immersive technologies developed a much greater range of approaches due to the exponential technological progress witnessed in such a short period of time. As was already mentioned, some of the most widespread applications go from home entertainment to health care, from manufacturing to training and education, and many more.

1.2 Definition of Immersive technologies and Mixed Reality

We have already dealt with some of the main definitions that researchers have provided about immersive technologies in the past decades. However, it appears that academics have not come to complete agreement when using proper terminology concerning all kinds of technology that can ensure some level of immersiveness. Terms such as Augmented reality (AR), Virtual reality (VR), Mixed Reality (MR), and Extended Reality (XR) are often regarded as overlapping concepts or even synonyms (Rauschnabel *et al.*, 2022), thus creating ambiguity and confusion.

> "If we don't all agree on the same definitions, then we have immediate ambiguity and confusion when we are talking about Mixed Reality, Augmented reality, or Virtual reality, which then requires further explanations and alignment which then leads to wasted time and energy and potentially misalignment of expectations and so on".
>
> (informant "MIKE", Head of XR for a leading consulting firm)

The following paragraphs will examine some of their main characteristics.

The most generic definition is given by Schmalsteig and Höllerer (2016). They make a clear distinction between technologies concentrating mainly on their relationship with the reality surrounding the users, i.e., AR supplements the real world by amplifying it with superimposing virtual objects to allow users to experience the real world at the same time. VR completely replaces the real world as a simulated experience, so that the user is totally immersed in a computer-generated environment. However, with regard to Mixed reality it is definitely more complex to reach a univocal interpretation; Speicher *et al.* (2019: 1) believe that "while there are prominent examples, there is no universally agreed on, one-size-fits-all definition of MR". Yet their study serves as a collection of discussions with fellow researchers and professionals in the industry on the matter. Milgram and Kishino (1994) were among the first researchers to suggest that AR exists along a continuum between both real and virtual worlds, hence they conceptualised Mixed Reality as an umbrella term for all those technologies where virtual and real elements blend together. As displayed in the picture below, the continuum, defined as Reality-Virtuality (RV) continuum, sees the Real Environment i.e., an environment built up only by real objects and everything that can be perceived by people in first person on the far-left end, whereas on the far-right end the Virtual Environment i.e., an environment which includes computer-graphics simulations is positioned. In this way, as Milgram and Kishino (1994: 3) state, "rather than regarding the two concepts simply as antitheses [...] it is more convenient to view them as lying at opposite ends of (the) continuum". Moreover, moving from the Real Environment (RE) side we get Augmented reality; by contrast, moving from the Virtual Environment (VE) side we get closer to Augmented Virtuality (AV). Lastly, Mixed Reality is defined as the space anywhere between the two far ends. However, Milgram and Kishino's continuum has been interpreted in various ways, one of which intends Mixed Reality as a kind of reality on its own situated between the AR and AV extremes (Farshid *et al.* 2018, Flaviàn *et al.* 2019).

In addition, Hoyer *et al.* (2020) define MR as an extension of AR with the sole difference that if the latter is mainly available through smartphone apps, MR requires a headset or an equivalent wearable device. With regard to the definition of the abbreviation of XR (commonly, but misleadingly, read as "Extended Reality"), its clear definition remains unknown, yet I will try to gather together scholars' most influential opinions in this section.

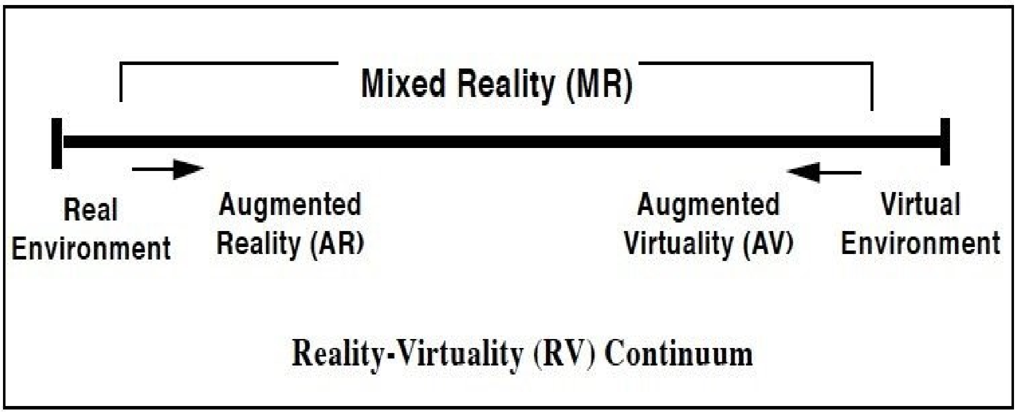


Figure 1.5: Milgram's Rality-Virtuality Continuum. (Source: Milgram and Kishino 1994)

The following paragraphs will expand on the concepts of Augmented, Virtual and Mixed Reality, adding some definitions and visual explanations to better understand their main differences.

1.2.1 Augmented reality (AR)

With regard to Augmented reality, its first example ever created in history has to be found in the "Pepper's Ghost" technique, a simple illusion that has been used since the second half of the nineteenth century mostly in Victorian theatres; it was named after John Henry Pepper, that is to say, the scientist who demonstrated the technique for the first time. Inventor Henry Dircks, on the other hand, started using this technique assiduously in theatres to make a ghost appear on stage. The effect is based on the use of a slanted half mirror where the original picture is reflected and eventually projected on stage (see the *Figure 1.6* for reference); thus, a virtual 3D image is created.

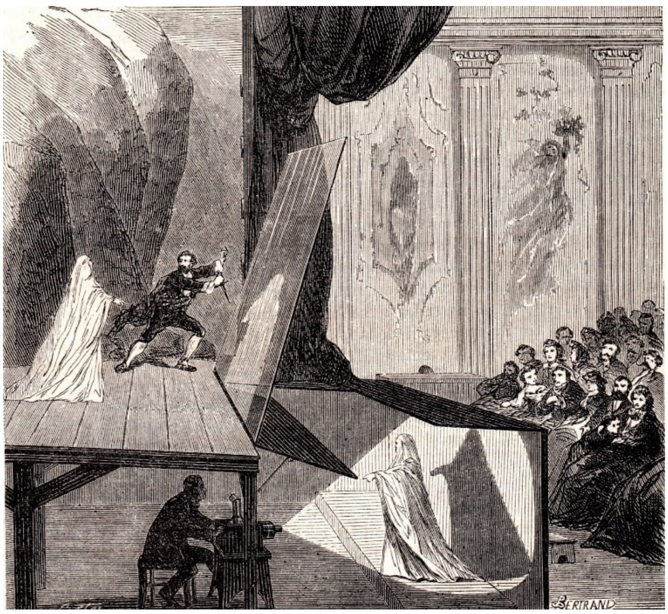


Figure 1.6: Pepper's Ghost technique on stage. (Source: rct.uk)

Furthermore, as Nakamura *et al.* (2019) observed, this technique allows converting everyday environments into screens displaying virtual images, e.g., a wall can be turned into a screen for a virtual-image-based video-communication system. However, it is worth of notice that AR, as already mentioned, superimposes digital elements with the real world, but does not allow any kind of interaction. By contrast, Mixed reality creates an environment in which virtual and real elements coexist simultaneously due to a computer's complete knowledge of the surroundings can be achieved through Mixed reality. In this way, an acceptable differentiation between these two types of concepts using similar technologies is established, although extant literature does not seem to be unanimous, with many incompatible or contradictory classifications. Furthermore, to achieve the aforementioned effect, as well as to recreate a more immersive environment, a great number of AR devices have been created in the past decades, and they will be attentively analysed in the following chapters.

1.2.2 Virtual reality (VR)

We can find the first ever hint of a virtually generated, technology-driven world in early science fiction and fantasy novels, as well as in panoramic paintings that make use of foreshortening[1] to create a more immersive environment for observers to make they believe they are really part of the scene (Bown *et al.* 2017). With regard to the first ever successful example of a VR device, Jeon (2015) considers it to be the Link Trainer application, namely a flight simulator built in 1929 and used to train World War II pilots, but originally destined for amusement parks.

[1] That is to say, "to draw, paint, or photograph people or objects to make them seem smaller or closer together than they really are". (Source: Collins dictionary)

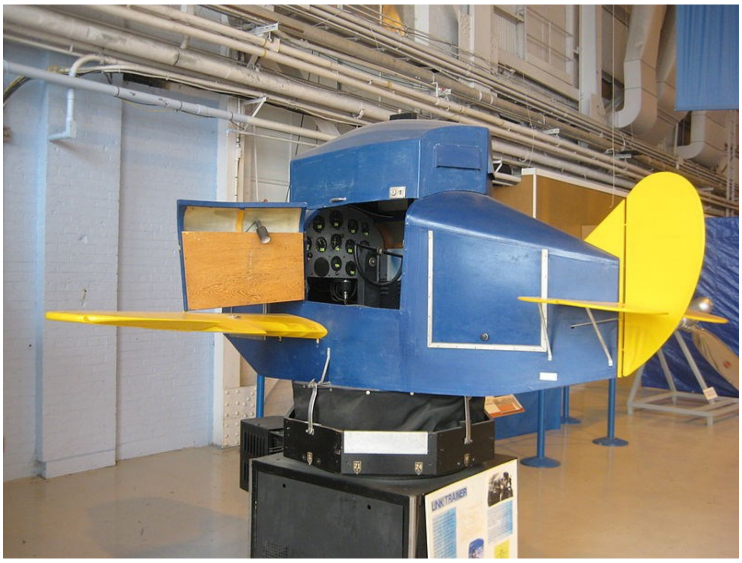


Figure 1.7: The Link Trainer simulator. (Source: anae.it)

As clearly defined by Milgram's RV continuum, there is no hint of the real world in the VR environment, which is therefore completely computer-generated. Experts refer to it as entirely synthetic and immersive, with a virtual view that has to be generated only through the help of head tracking or head-worn displays. This leads to a lack of social interaction between users, who are therefore regarded as "isolated" (Speicher *et al.* 2019). Moreover, as will be further discussed in the next sections, experts believe that one of the aspects that attribute great value to VR technology lies in its ability to reach such a level of immersiveness that, for instance, it allows users to travel to remote places and times without any physical need to move. This extends its main scope of action and makes it perfectly suitable to a large number of uses.

1.2.3 Extended Reality (XR) and some definition problems

There is no univocal definition of extended reality, due to experts' own approaches to terminology. A common statement, however, is that XR stands for an umbrella term that combines many different concepts, most certainly Augmented and Virtual reality, as well as Mixed Reality but only if intended as "a combination of AR and VR" (Rauschnabel *et al.* 2022). However, an unambiguous definition would benefit all the stakeholders mostly involved in the use and development of the various kinds of immersive technologies. To this purpose, first and foremost, current research needs to reinforce pre-existing studies aiming at identifying and explaining central differences between relevant terms and organising such concepts in a coherent framework (Rauschnabel *et al.* 2022).

With regard specifically to the definition of XR, extant literature affirms it stands for multiple meanings. Alcaniz *et al.* (2019) are among those who believe it is an abbreviation for "Extended reality", although other experts find this definition misleading as it does not take into account Virtual reality that, by definition, replaces rather than extends reality. On the other hand, a further theory refers to the letter "X" as a placeholder for any format of digital reality (similar to the algebraic variable *x*), therefore translating the whole meaning into "something R", which lives it the aforementioned function of an umbrella term. *Figure 1.8* helps to summarise and easily visualise the XR framework.

The following section will therefore get into more details about the main devices that can be helpful in XR picturing.

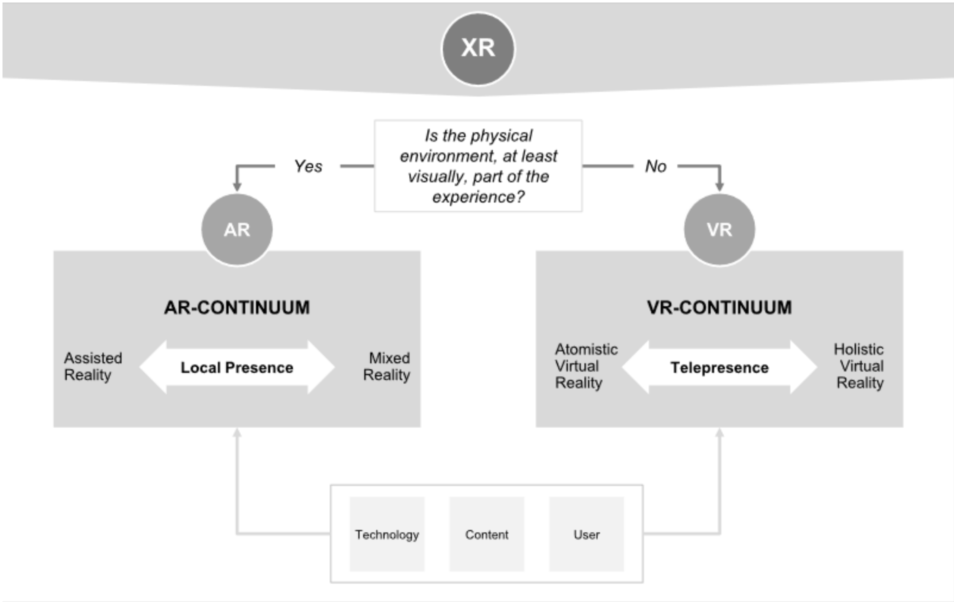


Figure 1.8: Synopsis of the XR framework. (Source: Rauschnabel et al., 2022)

1.3 MR devices

As a means to achieve a unique perspective that enriches the way real and virtual environments and mixed reality experiences are perceived by the human eye, the main concepts that have to be kept into consideration are "flexibility, immersion, interaction, coexistence, and enhancement" (Bekele *et al.* 2018: 5). This section will therefore focus on the main essential technical elements of AR, VR and MR applications. Firstly, I will focus on Milgram and Kishino's (1994) main taxonomy of MR devices. Secondly, my analysis will regard specifically features such as tracking and registration, virtual environment modelling, devices for input and tracking, and interactive interfaces.

1.3.1 Milgram and Kishino's taxonomy

In their 1994 essay, Milgram and Kishino preliminarily organised MR interfaces into six categories,

1. monitor-based (non-immersive) video displays such as "window-on-the-world" (WoW) displays;
2. monitor-based head-mounted displays (HMD);
3. head-mounted displays with a see-through capability allowing computer-generated graphics to the optically superimposed onto real-world scenes;
4. same as (3) but making use of video viewing of the real world, rather than optical scenes;
5. completely graphic display environments (partially or completely immersive);
6. a combination of a completely graphic but partially immersive environment, where real-world objects interface with the virtual scene, for instance when users have to grab something with their own hands.

What the two researchers (Milgram and Kishino, 1994: 6) want to highlight in this regard, however, is that:

> "Although the six classes of MR displays listed appear at first glance to be reasonably mutually delineated, the distinctions quickly become clouded [...], especially in relation to implementation and perceptual issues. The result is that the different classes of displays can be grouped differently depending on the particular issue of interest".

This statement underlines the urgent need for researchers to display an official taxonomy that considers all possible practical issues, aiming to disambiguate any kind of definition, as well as to align future research and developments. Consequently, this taxonomy can be regarded as "a starting point for discussion" (Robinett 1992: 230).

We will now concentrate on the main features of each section of the taxonomy, as all the elements that have been previously listed in Milgram and Kishino's taxonomy may be grouped into two further subcategories: devices can be, in fact, defined as wearable and non-wearable.

Wearable devices are Head Mounted Displays and are entirely devoted to AR/MR immersion; they can be both helmets and headsets.

- Helmets fully cover users' heads, ears, and eyes; some of their applications include, for instance, the implementation of motorbike helmets integrating information into the view ahead. In 2021, Swiss firm Aegis Rider AG created an AR helmet through which virtual limitless potential is achieved: it can provide real-time danger warnings and check cross references with online maps including information about speed limits and road characteristics. Such warnings could be displayed on the traditional dashboard. However, riders would have to take their eyes off the road increasing the level of danger.
- Headsets are regarded as smaller and definitely less invasive devices than helmets, as they do not entirely cover users' heads, but rather look more like glasses. The first prototype of smart glasses, Google Glass Explorer Edition, was released in 2013 by Google, and could provide users with pop-up news, notifications, texts, and navigation indications. It used touch and voice commands, but it was not connected to a cellular data network, and therefore it worked with a Wi-Fi connection only. AR was made available through a tiny square glass prism field to the glasses' frame, as it worked as a small screen to the viewers' eyes connected to a small projector that transmitted all the digital information required. The main aim was to create a minimal device suitable for daily use. Apart from smart glasses, visors are also part

of the headset devices; the most common ones are Microsoft HoloLens, which is going to be more thoroughly analysed in the following chapter, and Magic Leap One.

As to non-wearable devices, these are common applications that do not have MR immersiveness as their primary scope. Rather this category includes smartphones, computers, tablets, and televisions that function as MR supporters. Head-Up Displays (HUDs) represent a perfect example of this kind of devices. They were first used in 1958 in fighter planes, whereas nowadays they are employed mostly in vehicles. Their function is quite similar to the aforementioned headsets, as they give supplementary information to users who are therefore able to see without taking their eyes off the road. HUDs can project images on the windscreen, superimposing graphics onto the real world.

Figure 1.9: (from left to right) The first prototype of Google Glasses, and Microsoft HoloLens.

1.3.2 Essential aspects of IT applications: tracking

Bekele *et al.* (2017) have defined some essential features that are common to most devices, regardless of their domain, namely tracking, virtual environment modelling, computers, display, devices for input and tracking, and interaction interfaces. This section will be entirely dedicated to each of these aspects.

Tracking is defined as the determination of users' positions and is mainly required for AR applications, as this kind of technology seamlessly needs to superimpose virtual content over the real world, and the position of the AR device in relation to the real world has to be determined; on the other hand, VR requires such feature only when users' poses have to be tracked. Proper tracking is achieved through:

- Six Degrees of Freedom (abbreviated as 6DoF), namely the range of motion in which a rigid object can move in space; three of them refer to the orientation of users' heads (left and right, backwards and forwards, circular), while the others are related to the spatial movement (left and right, backwards and forwards, up and down);

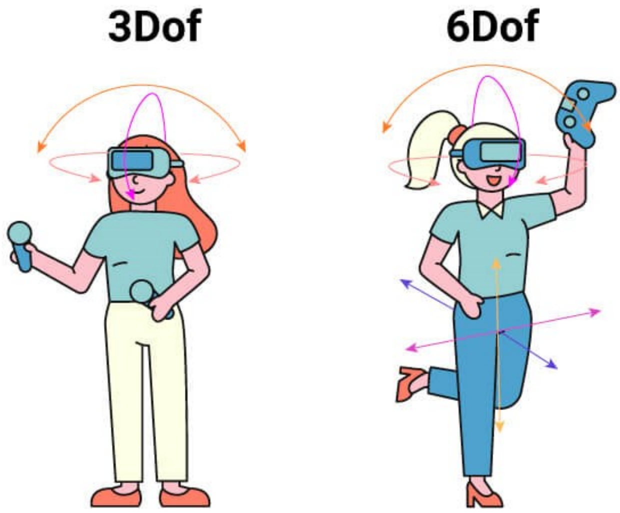


Figure 1.10: The Degrees of Freedom. (Source: mindpot.co)

- Three Degrees of Location in the 3D space, i.e., the x-axis, the y-axis, and the z-axis;
- Three Degrees of Rotation (3DoR), which means that no translational movements are allowed.

As defined on the Google VR web page, devices can have either 6DoF (e.g., Google's Daydream Standalone headsets) or 3DoF (e.g., Daydream View).

A further division is made when talking about the various typologies of tracking that can be camera-based (active tracking) or rely upon physical sensors from a distant location (passive tracking). Such different approaches will be further developed in the following paragraphs.

1.3.2.1 Camera-based

Camera-based technology is divided into three sub-categories:

- marker-based tracking;
- markerless tracking;

- infrared (IR) tracking.

The former relies on a digital camera, vision algorithms, and, most importantly, on easily recognisable indoor or outdoor landmarks, i.e., coloured patches, or a set of patterns that can be easily detected by a digital camera (Köhler *et al.*, 2010) to assure a high probability of recognition and a low probability of misclassification. Moreover, to function properly this kind of tracking needs good lighting conditions, which makes marker-based tracking less advisable indoors and in fields of application where fragile objects that could be damaged by the markers themselves are present (e.g., cultural heritage, as will be more carefully examined in the next chapter).

Markerless tracking is also defined as "vision-based tracking" and it works through detecting and noticing geometrical features in the real environment (e.g., building corners or edges) to create a connection between the 3D world and 2D image coordinate. As stated by Costanza *et al.* (2014), a training phase is required in markerless tracking, aiming at tracking the objects in the system from one or more points of view or angles. This clearly requires a large amount of processing; for this reason, the rendering could take a long time.

Figure 1.11: Some examples of visual markers. (Source: Köhler et al., 2010)

Infrared (IR) tracking allows for a real-time estimation pose of an object considering both the position and the orientation of markers that are always used in this kind of method. What has to be noted, however, is that if a single marker is attached to a target, it is possible to track only its position; on the other hand, multiple markers track both position and orientation. Furthermore, IR tracking is particularly effective as it is not affected by light conditions, therefore it is useful both for inside and outside registration.

1.3.2.2 Sensor-based

Bekele *et al.* (2018) divide sensor-based tracking into three categories:

- electromagnetic tracking;
- acoustic tracking;
- inertial tracking.

The former makes it possible to determine the distance, orientation, and depth of an object, as well as distributional change along various axes measuring the intensity of the magnetic field present between a base station and a measurement point. On a negative note, however, this system is subject to interference from other magnetic fields, which can be mitigated by installing the various elements in a controlled environment.

By contrast acoustic tracking uses ultrasonic sound waves moving from an emitter (usually attached to an HMD and other interaction interfaces) to a sensor to estimate the pose of a viewpoint. Again, a very noisy environment, may cause measurement errors by the tracking system; for this reason, acoustic tracking is rarely used alone, as it works more efficiently when combined with other tracking methods.

Lastly, inertial tracking calculates both pose and velocity measuring the rotation and motion of a given target through gyroscopes (they calculate angular velocity to know the target's angular rotation) and accelerometers (they measure linear acceleration to understand the target's position). However, the accumulation of small measurement errors from the gyroscope and the accelerometer due to positional drifts makes the data obtained not entirely reliable; hence, it would be more effective to fuse inertial tracking with other tracking systems.

An effective combination of multiple kinds of tracking is called hybrid tracking. It can yield better results than when each tracking system is employed separately. In particular, various combinations always include inertial tracking, as it grants better accuracy for orientation measurements.

1.3.3 Essential aspects of IT applications: virtual environment modelling

Virtual environment modelling is defined as "the process of simulating real objects and their state in a digital space, the behavioural rules that objects obey, and relationships and interactions between them" (Zhao 2009: 3). Bekele *et al.* identify several types both of 3D model data and reconstructing methods that will be examined in the following paragraphs.

With regard to model data types, authors list:

- actual measurement;
- mathematical measurement;
- artificial construction.

The former refers to the model acquired from 2D and 3D scanning, whereas mathematical measurements generate virtual representations of the real environment through mathematical models, experimental analyses, and abstractions. Lastly, artificial construction generates model data without any scanning from the real world, yet directly from human imagination.

A further categorisation of model data types is applied with particular reference to real-world associations, namely:

- spatial structure data, which regards the geometry of real objects;
- physical properties describing physical processes and changes of real objects, behavioural properties dealing with their behaviour, and dynamic properties, as well as motion data, referring to the deformation, collision, and motion.

Modelling methods taxonomy, on the other hand, is defined taking into account users' perceptions (i.e., visual, auditory and haptic modelling methods) and what the object looks like in the virtual environment (i.e., scene appearance, physics-based behaviour, and real-Virtual reality combined modelling). When deciding which modelling method to use, determining guiding factors are objects' complexities in the real world, users' expected modalities, and expected degree of model fidelity, therefore it all depends on the practical use the object it is destined to.

1.3.4 Essential aspects of IT applications: devices

The main devices that can be used for AR, MR and VR systems are displays, computers (essential for immersive-technologies systems as they make software tools run properly), tracking devices and cameras (used only in marker-based or markerless applications; they are combined together in hybrid tracking approaches), and input devices. The following paragraphs will analyse in more detail two of the aforementioned devices.

- Displays are presentation devices; therefore, their appearance is the most essential with regard to immersive technologies. They are categorised according to the kind of content they display, namely virtual, auditory or tactile. Authors also recognise several types of displays, some of which have already been mentioned in section 1.3.1.
- HMDs are further divided into optical-see-through and video-see-through, where the former allows users to see the real environment and the virtual world through a transmissive and reflective mirror; the latter combines virtuality and reality in the graphic processor of the computer.
- Spatial AR (SAR) projects augment reality by projecting virtual information onto the real world.
- Handheld displays are used in combination with digital cameras and inertial sensors, and again are able to superimpose virtual content over real environments.
- Desktop screens and projections are more suitable for non-immersive and semi-immersive VR experiences; multiple viewers can enjoy a 3D scene with stereo glasses.
- Cave Automatic Virtual Environment (CAVE) allows multiple users to experience a fully immersive 3D scene at once, as projection displays are hung on the walls of a room to replicate a cave-like cube.

With regard to input devices, on the other hand, a wide range of such devices is available, from desktop-based interfaces to more intuitive ones, i.e., speech, gaze and gestures. Input devices highly depend also on the domain and on the system of the application.

1.3.5 Essential aspects of IT applications: interaction interfaces

Immersive technologies greatly base the likability of their experience upon users' interactions; therefore, researchers’ main aim is to provide users with intuitive and natural interaction interfaces. A sense of presence is equally essential, as authors believe that the perception of being physically present in a virtual (hence non-physical) world is a key experiential aspect of VR technology. Not being aware of standing in a virtual environment is what makes the system really effective. Bekele *et al.* (2018) identified six different kinds of interfaces for AR, MR and VR, namely tangible, collaborative, device-based, sensor-based, hybrid, and multimodal interfaces.

- Tangible interfaces ensure an immediate manipulation of information between physical and virtual objects, similar to AR applications. Full potential allows physical objects to be augmented directly, yet it is allowed to use physical objects to interact with virtual ones, too.
- The main feature of collaborative interfaces is their need to use multiple displays at once while allowing users to see the virtual information from their perspective to make it more realistic. Remote collaboration is possible, too, with the use of HMD to cooperate in a common virtual space. Device-based interfaces include, among others, haptic interfaces, gamepads, mouses, joysticks and many others.
- Sensor-based interfaces such as motion tracking, gaze tracking, and speech recognition make it possible to detect the flow of interaction commands.

- As can be easily understood, hybrid interfaces combine various kinds of complementary interfaces simultaneously, and each combination should be associated with a different type of device. Collaboration between users is a key element of hybrid interfaces, which may lead to some difficulty in defining the main differences between collaborative and hybrid interfaces. What has to be borne in mind is that while hybrid interfaces may allow a single user, collaborative ones, by definition, cannot. This inevitably makes hybrid interfaces much more common.
- Lastly, multimodal interfaces are defined as "a fusion of two or more natural interaction modes" (Bekele *et al.* 2018: 13), and it perceives natural interaction modalities of humans through sensing devices.

1.4 Fields of application

This section will present a general overview of the main fields in which immersive technologies have revealed their uses and proved themselves to be fundamental in the enhancement of a wide range of activities.

Over the last decades, Virtual reality and immersive technologies as a whole have moved from being limited only to the gaming area of research, to a wider range of professional development and applications (Kaminska *et al.* 2019).

1.4.1 AEC industry

The Architecture, Engineering, and Construction (AEC) industry has been developing a great number of implementations due to the recent immersive-technologies application in this field. Noghabaei (2020) asserts how the AEC industry is quite new to this collateral support in the United States, notwithstanding its great impact on the economic growth of the country. To limit the increasing cost of overruns and delays of construction projects mainly due to the lack of communication between the construction parties and the difficulty in finding the right support in advanced communication technologies, AEC industries made good use of Building Information Modeling (BIM), namely "the process of generating and involving a digital representation of a building or construction and their characteristics" (Noghabaei 2020: 2). Despite its fundamental role in organising, enhancing and visualising AEC projects, BIM had some insurmountable shortcomings that began to clash with its purposes. To answer some of the aforementioned deficiencies of BIM and guarantee a further and more effective enhancement in AEC, researchers eventually opted for the new pioneering advantages coming from immersive technologies. Alongside his study on the AEC industry, the author dedicated part of his research also on investigating applications of AR/VR technologies in other domains, with the main scope of comparing them to AEC and find further potential uses. Some of the most relevant uses will be hereby discussed.

1.4.2 Retail industry

The retail industry has been aided by Mobile Augmented reality (MAR) applications, which added a more experiential value to consumers' shopping, developing the concept of "smart retail" (Dacko 2016). The results proved that both consumers and retailers declared to have received more benefits from this kind of shopping experience than the common one (e.g., in terms of purchase satisfaction, efficiency, and increased purchase), and small retail, too, could benefit from such a service.

1.4.3 Work-related accidents prevention

Immersive technologies are also able to solve important problems related to other people's lives, often connected to dangerous working conditions or severe limiting diseases. For this same reason, the mining industry places itself as one of the pioneering industries in adopting such technology, as accident-at-work statistics regard it as one of the most dangerous industries. The case reported (Grabowski 2015) considered a pilot study on the training of coal miners using various kinds of VR devices and input methods, proving their effectiveness both as substitutes for on-site training, as well as methods to prevent young future miners to endanger their lives at an initial phase of their job.

1.4.4 Healthcare industry

The Healthcare industry certainly belongs to those where immersive applications are able to allow sensible aid to the people involved. Anxiety (Mosadeghi *et al.* 2016) and pain level (Tashjian *et al.* 2017) cases have been taken into analysis, resulting in quite significant conclusions about relieving uncontrollable tensions through distracting, game-like experiences (Mosadeghi *et al.*'s patients explored the ocean and travelled around Iceland through VR simulators; Tashjian *et al.*'s managed to actively control their subjects' heart frequencies and blood pressure when they were in physical pain in a 15-minute VR simulation called Pain RelieveVR). In addition, Dascal *et al.* (2017) stated that the healthcare areas in which immersive technologies prove to obtain the best results are eating disorders, pain management, and cognitive and motor rehabilitation, as well as neurosurgery (Pelargos *et al.* 2017) as these past years have proven.

1.4.5 Education

Education is without any doubt another area of interest for immersive-technologies researchers. Among the most common benefits deriving from such a combination, studies have proven the enhancement of learning achievements and motivation in students, allowing them to be involved in the authentic exploration of the world (Dede 2009) and to increase their investigation skills (Sotiriou *et al.* 2013). A wide range of surveys has also proven that most students remembered more clearly what they saw in an immersive environment, concluding that, for instance, VR is a more memorable environment rather than laboratory-based tests (Kaminska *et al.* 2019). In addition, the level of immersivity reached in such contexts demonstrates also increasing creativity in the design outputs (Noghabaei 2020); it also worked as an aid for university students, whose practical skills are positively influenced by these technologies (Kaminska *et al.* 2019), through which they may develop a stimulating mindset when it comes to laboratory work (Akçayır *et al.* 2016).

To guarantee a more complete overview of these kinds of applications, it would be useful to present a taxonomy of VR applications in education, dividing the devices into three categories according to their level of immersion, as presented in Kaminska *et al.* (2019).

- VR environment created with a stereoscopic display and mouse/keyboard is used to present a state of theoretical knowledge to students, thus requiring a less immersive environment compared to other devices. Wall-based or monitor-based projections with special goggles or simple HMDs are the most commonly used tools to achieve such a level of immersivity. A detailed overview of the various situations in which such use has proven effective for students is given by Black (2017). For instance, he presents the boundless potential of VR in history teaching, taking into analysis Google Expeditions, a smartphone app that allows teachers and students to go on virtual trips around the world. To enjoy a 360° panorama, students' smartphones are paired with a cardboard HMD that is in turn synced with a tablet through which the teacher can control both the scene and the environment. Students could "move in time" and make it a communal activity. Arnswalde VR (2016) developed by Odessey VR Studio is similar to Google Expeditions. This immersive experience recreates the Polish city of Arnswalde (today's Choszczno) which was on the front line in 1945 during WWII; due to its strategic position the town was almost completely destroyed, which lead to its reconstruction at the turn of the twentieth century. Using this app, however, people can visit the city and see with their own eyes what it looked like before the war, seeing buildings and experiencing a place that no longer exists. Lastly, this kind of VR technology results in a useful application in safety training situations (i.e., firefighting, traffic accident, and natural disaster); children can learn how to deal with dangerous situations and receive the right preparation in case of real-life emergencies.

- Experience room, on the other hand, is a platform that focuses on the acquisition of practical skills by students who have previously gotten the necessary theoretical knowledge to apply it on practical tasks. The level of immersion, in this case, is extremely higher than in the previous one, and users also have more control over the device. For this purpose, some special external sensors might be required. Zhang *et al.* (2018) present an innovative way in which Microsoft Kinect might be used in educational laboratories creating Virtual Environments (VE) through 2D cameras and 3D scanners, achieving a Kinect-based object tracking, and synchronising human body motion and the avatar. To guarantee a complete experience, it is important to develop suitable speech recognition and voice commanding, which can help students in getting started with the VR platform. In addition, sensor gloves or haptic suites can be considered essential devices to reach such a kind of immersion, as they may help simulate task-specific training in dangerous work environments. HMDs can also be used to enhance the realism of the simulation. Lei *et al.* (2018) conducted an exploratory study investigating how VR can facilitate children's learning processes in scientific disciplines; when learning 3D geometry, for instance, children find it often difficult to continually convert between the 2D figure in their book and the 3D model in their mind. The same difficulty arises when they have to solve motion problems, as they have to imagine the whole moving process in their mind, which may cause them some confusion. As a solution, VR can allow children to directly observe 3D models in real life, and they can actually watch precise movements; in this way, VR offers a more effective and fast learning method for children, and it improves their learning performance.

- VR platform that teaches problem-solving given a determined knowledge beforehand. This kind of application is particularly oriented toward medical sciences and engineering students who have to develop high problem-solving skills when facing a specific phenomenon that has to be analysed and synthesised to formulate an action plan and value the overall situation. As situations might be unique according to each scenario and vary from time to time, high-precision educational systems may have to support tailor-made haptic interfaces, which undoubtedly may raise costs. Some examples of applications in this regard are Mahdi & Akin's (2021) study on a virtual training tool for electrical engineering education where users can connect and modify the 3D models. Moreover, it allows engineers to test machines under extreme conditions, which is of course not possible when working with real devices. These kinds of applications, in addition, reduce the necessity of abstract thinking when dealing with complicated concepts about mechanical or electrical engineering (Kaminska *et al.*, 2017).

Besides this classification, Kaminska *et al.* (2019) add a further taxonomy to divide VR educational applications. The further aspects that should be taken into account are the autonomy of the devices (whether they can be used by students autonomously or they require the teacher’s help), their final user (teacher or students), their purpose (to learn, to practice, to train, to implement memorization), and their place of use (at home, in the classroom, in specific laboratories).

What has to be noted, however, is the lack of reference to AR/VR studies related to younger elementary students, as Freina and Ott’s study (2015) has demonstrated. The tendency to not take into consideration the possibility to conduct some sort of analysis in younger children might be due to the fact that their growth is not yet completed, therefore 3D vision, hand-eye coordination and balance are still to be fully developed, making it difficult for researchers to process clear and unbiased data. For this particular reason, in the “health and safety warnings” section of the Oculus Rift manual, it is highly recommended for children under 13 years of age not to use the device. What makes it challenging for schools and teachers to allow full use of immersive experiences in the educational framework are limitations concerning economic resources required to distribute equally all the technological components needed (Kaminska *et al.*, 2019).

1.4.5.1 People with disabilities

Another important aspect regarding the use of immersive technologies in the educational setting that has to be taken into account is their use when interacting with people with disabilities. Virtual reality is believed to be perfectly suited for these kinds of needs as “it removes stimuli from the environment, manipulates time (allowing for short breaks), and allows subjects to learn while playing” (Oliveira *et al.* 2007: 134). Freina and Ott (2015) report only on a few studies on the matter, dating back to the early 2000s: in 2005, Standen *et al.* used VR for rehabilitation of people with intellectual disabilities; Tae-Young (2013) analysed the positive impact of the use of a HMD by people with disabilities in various situational scenarios, managing to learn quickly the more they practised, as well as improving their mental and adaptive capabilities; Matsentidou and Poullis (2014) used a CAVE based system for educational applications of children with Autism Spectrum Disorders (ASD) (specifically, the main purpose was to teach them how to safely cross at a pedestrian crossing autonomously). Lastly, a further paper (Jones *et al.*

2014) is mentioned regarding an application created for students with hearing disabilities who could wear smart AR glasses to see the translated speech they were not able to hear in ASL (American Sign Language).

However, what is worth noticing now is that the rapid technological evolution that took place in the last decade made it possible for AR/VR devices to be exponentially more helpful in improving the lives of people with mild to severe forms of disability. In her article published in 2022 in the online magazine ARPost, Czech journalist Georgana Mileva collected some of the most relevant and recent applications of immersive-technologies devices studied in this matter dividing them into different forms of disability.

- Visually impaired individuals can "see" (or rather feel) famous artwork in great detail with the help of VR haptic gloves (Avatar Haptic Gloves by the Czech exhibit "Touching Masterpieces") that use vibration to make people recognise the shape of objects and their details. In addition, colour-blind people can correct their disease with Chroma, "a wearable augmented-reality system based on Google Glass that allows users to see a filtered image of the current scene in real-time" (Tanuwidjaja *et al.* 2014: 1). Lastly, when simple and banal actions such as watching television become impossible for people with low vision, technology may actively help with the VR Vision Buddy hub installation that makes it possible to make everyday life actions more accessible; Vision Buddy is a pioneering Silicon Valley start-up that was founded in 2020.
- People with ASD who lack interactive social skills finding themselves in awkward and overwhelming situations can overcome this great difficulty of

theirs with Empower Me, an AR environment that uses the Brain Power System technology. With its characteristics, it allows users to connect with the world around them through a non-intrusive smart display that encourages social conversation with others by keeping eye contact with the interlocutor, as well as by leaving users' hands free to move and their heads up to allow a more efficient engagement with the people surrounding them. In addition, VR technology is employed by Project VOISS (Virtual reality Opportunities to Integrate Social Skills) to simulate social interactions and make it easier for people with ASD to learn how to deal with them in real-life situations. Project VOISS offers a large number of scenarios in an open virtual environment, as well as a variety of characters to choose from to interact with.

- One of the biggest challenges concerning people with speech and hearing disabilities is communicating with the rest of the world. For this reason, researchers have proven that assistive wearable-tech devices are the perfect solution. For instance, UCLA bioengineers have devised a glove-like sign-to-speech translation system that is able to convert American Sign Language into English speech through a smartphone app lifting any kind of communication barrier (Zhou *et al.* 2020). During the analysis of 660 sign language hand gestures recognition patterns, this wearable translation system grants high sensitivity and fast response time to ensure real-time translation from signs into speech. Researchers also managed to capture facial expressions that are essential to convey important information in ASL adding adhesive sensors to testers' eyebrows and on the sides of their mouths. Lastly, communication is facilitated for people with hearing disabilities through the Augmented reality Sign Language (ARSL) mobile app developed by three NYU Tandon School of Engineering graduate students; this app allows for translation between many different sign languages as well as from spoken language into signs and vice-versa, making the interaction between hearing and hard-of-hearing people efficient. In this way deaf users can be more independent in everyday life, as well as when finding themselves in foreign countries, since there is no universal sign language.

- Lastly, a final form of disability is taken into account, i.e., dementia. In this case, AR and VR devices serve the purpose of increasing empathy for patients affected by this disease. Alzheimer's Research UK developed "A Walk Through Dementia" (2016), a unique app for Android smartphones aiming at raising awareness of what it is like for people to live with dementia. The app uses a combination of computer-generated environments and 360-degree video sequences to simulate how difficult it can be for patients to complete everyday tasks, from going to the supermarket, to orienting on the way back home, or even remembering where the rooms of their own house are located. The scenarios portrayed in the app have been created following the guidance of people living with various forms of dementia, to make them as similar as possible to reality. Furthermore, the app can work with a cardboard Virtual reality headset to create a more immersive experience.

CHAPTER 2
AR and VR applications in the cultural heritage framework

The employment of Augmented and Virtual reality in Cultural heritage (CH) sites is part of the development of brand-new frontiers with regard to tourist experiences and the spreading of the idea of smart tourism itself. Without any doubt, immersiveness plays a fundamental role in enhancing visitors' engagement, granting a much more effective and permanent experience regardless of tourists' age and cultural background, as it is becoming increasingly more common for people to look for experiences that allow a combination of both learning and having fun through a captivating engagement.

After a general analysis of the main fields of application of MR technology conducted in the previous section, this chapter will mainly focus on the importance this kind of technology has on tourism and cultural heritage sites, as well as on the impact it has on visitors. Once more general and technical details will be evaluated, some practical examples of existing applications in this regard will be discussed.

2.1 Smart tourism: a definition

UNTWO (Tourism World Organisation, namely the United Nations agency that promotes responsible and sustainable tourism) describes tourism as "a social, cultural and economic phenomenon that involves the movement of people to places outside their usual environment"[2]. Until the 1990s, mass tourism was its most spread form, which has then been replaced by cultural tourism; the latter sees tourists demonstrating a different approach with regard to their destinations, and a strong will to actively create experiences while travelling (Lee *et al.* 2020).

By its definition and most recent use, the word "smart" has been used to describe "technological, economic and social developments fuelled by technologies that rely on sensors, big data, open data, new ways of connectivity and exchange information" (Gretzel *et al.* 2015). Smart tourism is therefore defined as the adoption of the latest information technologies, making the overall experience more enriched, efficient, and sustainable. These new applications permit collecting enormous amounts of data, creating content for tourists and all stakeholders, enhancing visitors' experience, and improve social and environmental sustainability (Dorcic *et al.* 2017). With the increasing development of mobile technologies in the last decade, as well as with the Internet of Things (IoT) becoming crucial in creating pervasive environments, tourism has been influenced deeply. This has led to the creation of an effective infrastructure (rather than an individual information system) that integrates hardware, software, and network components to provide real-time consciousness of the real world (Gretzel *et al.* 2015). Furthermore, the intrinsic nature of tourism, which is primarily based on

[2] Source: https://www.unwto.org/glossary-tourism-terms

movement through time and space, makes the merging of both IoT and tourism quite effective, as it may allow visitors to move virtually through all the possible dimensions creating a new level of exploration. Such an implementation has even provided some practical benefits to cities during the COVID-19 pandemic, with powerful ICT services (e.g., immersive remote tours of famous museums around the world) employed to enhance the connection between some destinations and remote visitors. Further examples of this kind will be provided in section 2.5 of this chapter.

Whenever talking about smart tourism in extant literature, it is often mentioned its compelling ability in determining whether a city or a cultural heritage installation is worth visiting or not, being particularly influential on the travel experience and tourists' decision-making process (Lee *et al.* 2020). Some (Koo *et al.* 2016, Lee *et al.* 2020) mention destination competitiveness as an aspect that determines the significance of technological implementation tourism goes through. Smart tourism plays a fundamental role also in optimizing sustainable environments (Lee *et al.* 2020), which is key when considering that tourism is often perceived as an invasive activity (i.e., tourist overcrowding) from residents' perspective. This solution may foster the enthusiasm towards a particular destination, as well as allowing more environmental-friendly experiences. For this reason, it is essential to gather together citizens' opinions on the level of the liveability of their city to collect as much information as possible to reach proper results with the optimisation of cities through technology.

A further interesting aspect mentioned by Gretzel *et al.* is how the concept of smart tourism is susceptible to changes according to different parts of the world.

Researchers note that the Chinese and South Korean governments are more willing to focus on building more technological infrastructures to support smart tourism; by contrast, Europe sees a strong connection between the phenomenon of smart cities (i.e., the effort in enhancing cities with technology to reach sustainability, quality life and resource optimisation) and smart tourism itself through the enhancement of already existing tourism applications. Lastly, smart tourism is perceived in Australia as a way to enhance the economic potential of the country, as well as the experiential involvement.

2.1.1 Gamification, a short definition

What has to be noted, moreover, is that the concept of smart tourism can be easily connected with the one concerning the idea of "gamification". This term was coined in 2002 by game designer Nick Pelling to refer to the application of videogame mechanisms in social-life contexts, i.e., marketing, healthcare, education, cultural heritage and many others (Ursyn 2013). Its popularity in the last decades was due to its approach that aims at modernising and establishing a more captivating engagement among the contents related to a specific field and users, who are therefore moved by increasing confidence, as it happens in video games.

Although extant literature does not offer many examples of studies of this kind, some researchers as Xu *et al.* (2016) have begun to investigate this topic, specifically in relation to tourism and cultural heritage. In their opinion, playing games when visiting new cities and sites allows curiosity to grow, and therefore it is possible to collect as much information as possible about the destination in a fun and stimulating environment. Garcia *et al.* (2017) also talk about the positive impact gamification has on Destination Management Organizations (DMOs), of the kind of a much more encouraging engagement and enthusiasm, as well as a way to enhance the experience as a whole. They also believe gamification is key in increasing the visit duration of Points of Interests, balancing the distribution of tourists around the destination involved.

2.2 MR acceptance by visitors

Despite the benefits mentioned above, it appears as if smart tourism and, most specifically, MR in tourism have been appearing in such an environment more slowly than expected; this is also due to the existence of a strong relationship between the consumers' abilities in using the internet and the effective use of mobile applications (Douglas and Lubbe 2013).

Extant literature reports a lack of empirical studies that would be relevant in the determination of possible causes behind such a trend; however, Chung and Han (2015) have outlined three main reasons for users trying to avoid MR installation when visiting tourist attractions. Such a distinction by the aforementioned researchers would not have been possible without the attentive analysis of relevant studies on information technology acceptance (e.g., Gelderma *et al.* 2011, Gu *et al.* 2009, Lee *et al.* 2012). The criteria that have been taken into account to define the positive attitude visitors have toward AR in the cultural heritage domain include, among others, how easy to use are AR devices, whether the use of technology is really relevant and whether it sensationally enhances the tourist destination; this should develop tourists' will to visit the site again because they found it enjoyable enough. These reasons are described as follows:

- The personal propensity toward AR is the first aspect to be analysed, and it refers to the concept of technological readiness (TR), i.e., what is the visitors' overall attitude towards a never-been-used device. TR is therefore believed to affect users' beliefs, which is fundamental in such a context (see section 2.2.2 for reference).
- Visual appeal associated with AR is then taken into consideration, as visitors mostly aim at meaningful, functional, yet aesthetic information when travelling; the concept of beauty is determinant in the overall experience, therefore studies believe that if AR implementations allow cultural heritage sites to improve their level of attraction, they would be definitely more accepted by visitors. This is the same psychological process that influences consumers' interest in online shopping relying only on pictures they see on the web (Van der Heijden 2003). Such mindset refers totally to the Technology Acceptance Model (TAM) that will be further discussed in section 2.2.2, but that relies entirely on the perceived usefulness and on the perceived ease of use of the device.
- The situational factor is the last aspect to be taken into account, and it is strictly connected to finding a way through which external environments can help visitors to use a new IT device. Specifically, if users feel like the surrounding environment is adequate for using technology, then they are more prone to use it because they actually understand the need to. Facilitating conditions (e.g., tourists' previous knowledge of MR applications, short preliminary training before the actual use, and availability of an assistant to help with the MR application involved) are

therefore powerful means to enhance the ease-of-use of the technology (Chen and Chan 2014).

As a result, Chung and Han (2015) believe that the working method that should be followed when it comes to visitors' involvement has to firstly identify important factors that could stimulate tourists to use AR applications; secondly, it is important to investigate how the aforementioned factors influence visitors' beliefs, attitudes, intentions, and the destination visit intention.

2.2.1 An overview on the impact technology has on senior users

Although the research project that will be illustrated in the following chapters of the study relates to a group of young students, I think it would be helpful for the purpose of a more general overview to refer to the impact technology for tourism-related purposes has on senior users (i.e., above 55 years of age). As Davis *et al.* (1992) suggest, intrinsic motivation has to be considered alongside extrinsic reasons (usefulness) when determining the intention to use technology. Therefore, with the average population age increasing, together with the rapid spreading of information technology, many researchers have analysed this aspect (e.g., Phang *et al.* 2006, Smith 2008, Kim *et al.* 2015).

In this respect, the concepts of ease of use, usefulness, enjoyment and attachment have to be taken into account. With regard to the former, it refers to the acceptability by users of a new technology that is easier than others, as an easy-to-use system requires less effort on the part of the user. It is possible to say that ease of use is strictly correlated to the concept of usefulness (i.e., the extrinsic parameter) as it acts as its determinant; the same applies to enjoyment (i.e., the intrinsic parameter).

Lastly, with regard to the concept of attachment, researchers have shown that motivation has significant effects on it when it comes to tourist destinations and the involvement of technology. Therefore, I can assert that the more users are motivated, the more inclined they are to feel attached to a certain kind of technological device or experience involving technology, although this might be distant from their usual activities and mindset because they are not used to dealing with them on a daily basis (as, on the other hand, it happens with younger generations).

Kim *et al.* (2015) also give great importance to knowledge, as it “mitigates the impact of age on learning”, increases various kinds of interests and mitigates anxiety when dealing with never-seen-before devices in new contexts.

2.2.2 Technology Acceptance Model and Technology Readiness

we have already mentioned the importance of the Technology Acceptance Model (TAM) also related to the cultural heritage framework, as the two major beliefs suggested by TAM (perceived usefulness and perceived ease of use) are believed to be part of a standard that aims at reaching conciseness and predictability in a large number of fields (Davis, 1989).

Alongside TAM, another important concept that is strictly related to the former is Technology Readiness (TR) which is defined by Parasuraman (2000: 2) as “people’s propensity to embrace and use new technologies for accomplishing goals”. TR also refers to the state of mind proper to visitors once certain enablers and inhibitors are activated to determine users’ predisposition towards technology. Parasuraman identified optimism, innovativeness, discomfort, and insecurity as the dimensions through which measure people's attitudes toward technology. A brief definition of these dimensions is provided below:

- optimism is defined of course as a positive approach to technology and as the belief in the usefulness and efficiency role of technology in people's lives;
- innovativeness is a person's pioneering attitude with regard to technology;
- discomfort is a person's inability to deal with technology and a sense of related inadequacy;
- insecurity can be defined as a high-level scepticism toward technology.

As could be easily noted, a higher level of optimism and innovativeness enables more effective use of technology in relation to a wide range of frameworks. However, as Huang *et al.* (2007) noted if depicted as a continuum, the general users' attitude towards technology only ranges from a strongly positive to a strongly negative one.

Chung and Han (2015) report a further approach provided by Huang *et al.* (2007) with regard to TAM and TR combining both models, which implement each other. Indeed, researchers noted how TAM lacked the possibility to explain consumers' technology acceptance in their role of high-involvement users (therefore TR's aim), as it is designed only to approve technological use in an involuntary environment. In this way, TRAM (i.e., the combination of TAM and TR) makes it possible to understand the consumer adoption of e-services, in that TR functions as consumers' impressions on general technology, whereas TAM represents their ideas on a particular system.

2.3 Restoration cycle

Before proceeding with the following sections about future perspectives and practical examples of the employment of MR technology in the cultural heritage framework, it would be appropriate for the purpose of this work to give some further information on the use of this kind of technologies particularly with respect to the real archaeological item that is then translated into the virtual world.

In this respect, Saggio *et al.* (2011) made some interesting considerations about the strict connection that intertwines both reconstruction and restoration techniques and the Reality-Virtuality (RV) Continuum that was previously discussed in section 1.2. They assert that each stage of the restoration cycle is strictly correlated to a specific step in the RV continuum as reported in *Figure 2.1*. It demonstrates that starting from the real status, we move on with an analysis of the current status of matters (i.e., the Augmented reality status) that is followed by a virtual restoration or reconstruction of the artefact taken into account in the augmented virtuality stage to produce a complete virtual representation of the reconstructed scenario, that is to say, the virtual environment part of the continuum. Saggio *et al.* (2011) assert that all these stages are finalized at reaching the best possible results in converting reality objects (or parts of them) into virtual ones. To confirm their theory, researchers listed a series of reasons that prove this assessment right: they noted how AR allows restoration and/or reconstruction time, as well as related costs, to be reduced; physical work performed both by men ad machinery is indeed employed only in the final stage of the restoration cycle, which allows also energy consumption to be saved.

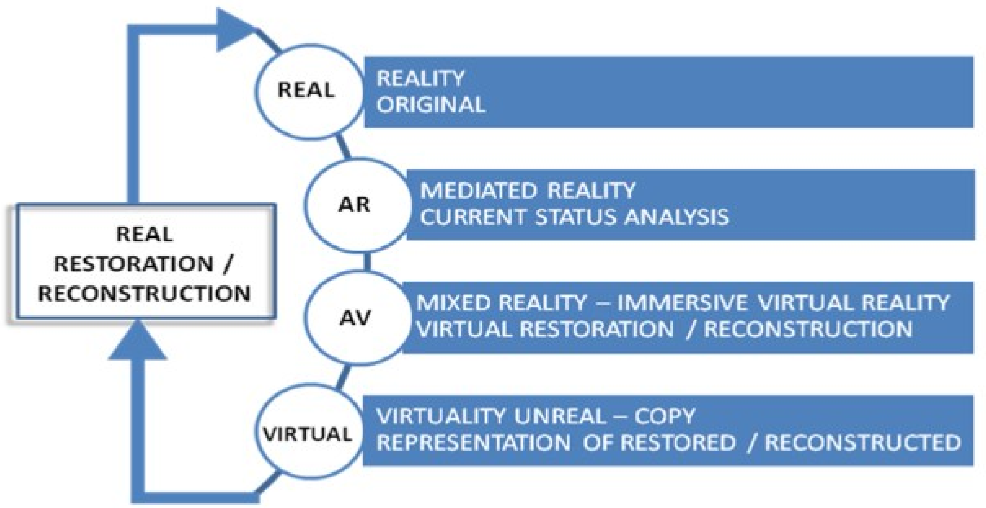


Figure 2.1: RV continuum and restoration cycle. (Source: Saggio et al., 2011)

AR also prevents potential breakages and reduces the risk of destruction of fragile yet v ble archaeological objects, but also potential abrasion and colour fading. Moreover, incomplete alua artefacts that may lack of some parts that have been lost or broken in the course of history may get their original form back through digital reconstruction; this is strictly related to the possibility of assembling the artefacts more easily once they have been found damaged in the excavation site. Lastly, researchers also evaluate the importance of 3D scanning as a procedure that allows the possible creation of a database that can be adopted for cataloguing reasons, tourism promotion or comparative studies.

Furthermore, the evolving situation of the artefacts restored during the cycle is presented, as the following models are identified:

- the original model refers to all those artefacts that have survived intact through the course of time without being damaged, therefore now they appear exactly as they were in the past;

- the state model refers to the actual situation of the artefact, namely its original model integrated with potential additions that improve it.
- The restoration model sees the original artefact to which manual interventions have taken place to resolve possible damages that happened over time; the aim is therefore to bring the artefact back to its native status.
- Lastly, the reconstruction model is made necessary once the artefact cannot be brought back to its native status only through restoration (i.e., manual intervention or additions), as little remains of the original artefact that is therefore complicated to define. The interventions that have to be considered do regard a full rebuilding of the artefact almost from scratch, with only the scarce original remaining as a track to be as faithful to the original as possible.

However, although effective and capable of changing the paradigm of the cultural heritage framework with respect to the fruition of the artefacts, what has to be borne in mind is that this technology is not immune to criticalness. Researchers, therefore, tried to make a clear distinction between the most relevant critiques: on one hand, they highlighted the need to have powerful calculation systems and rapid data transmission to grant effective interactions; this is strictly connected to the need to have a rendering software that could allow a high level of photorealism in real-time. With regard to the immersive experience in itself, it can be achieved only if virtual light, audio and haptic conditions as similar as possible to reality are created and calculated simultaneously; this can be achieved only by measuring light conditions through webcam images applied virtually to the real set. Furthermore, tracking has to be as efficient as possible, and this has to be granted in all possible different environmental conditions. Immersion is clearly enhanced only when video, audio and haptic devices are available to be worn also by people with limitations.

During the course of the experiment, as reported in the next chapter, participants will be asked to pay particular attention to these possible limitations to understand how close to reality the 3D models that they will see through an appropriate AR device are.

2.4 Future perspectives and negative aspects

Lastly, I think it would be worth mentioning part of the most recent literature that gives an interesting view about the future of technological applications in tourism, examining also part of their downsides. Buhalis (2020) believes in the increasing future cooperation between both suppliers and intermediaries of tourist services, to create a dynamic network able to interconnect everybody within an ecosystem. This would make it possible to enhance both inclusiveness and accessibility for travellers. Moreover, in the next decades an effective interconnection between the various technologies employed in smart tourism (e.g., AR, VR, fifth-generation mobile network, Cryptocurrency and Blockchain, and many others), together with improved computational capabilities supported by Artificial Intelligence (AI) and Machine Learning (ML), will be able to empower a constantly evolving dynamism between real and virtual worlds granting effective cooperation.

However, researchers also indicate some of the downsides related to technology applied to tourism in its wider meaning. Buhalis cites Townsend (2017) referring to ethical dilemmas such as privacy issues, failing systems, digital exclusion, information loss, and threats to languages and cultures. Furthermore, such a rapid evolution could lead to innovations too ahead of their time, leading to a lack of popularity among consumers, and scepticism.

2.5 AR applications in tourism and cultural heritage

This section will explore Augmented reality applications in the smart tourism framework: firstly, a brief introduction to the general use of this kind of technology will be given, therefore I will illustrate some practical examples of projects applied in real life to some specific scenarios.

Digital technology has become necessary when it comes to competition in tourism, as modern tourists are increasingly more difficult to attract (Katkuri *et al.* 2019). As I have already asserted in the previous sections of this chapter, the trend of smart tourism completely relies on state-of-the-art technological advances, which are oftentimes of the kind of Virtual and Augmented reality. When conforming these technologies to tourism and cultural heritage, they are proven to be effective as they permit digitally reconstructed artefacts or sites, allowing also for real and reconstructed ruins to fit together in harmony, as visual interference is avoided (Mesároš *et al.* 2016). Moreover, visitors can personalise their views (e.g., to visualise more than one state if several changes have been performed through the history of the artefact or monument considered), and a deeper connection between users and artefacts is established. Easy-to-use AR applications might also be effective in giving essential information about tourist destinations enhancing the experience of planning, interacting, and accessing essential information.

With regard to the devices employed, Mesároš *et al.* (2016) assert that firstly AR applications related to tourism and cultural heritage relied entirely on common MR devices (e.g., HMD) that added a camera simulating visitors' first-person view in real-time. The use of HMD has rapidly become obsolete due to issues related to time limitation, financial investment and the need for tourists' preliminary training and explanation with respect to the functioning of the device. Henceforth, at present time these devices have been almost entirely replaced by mobile devices, i.e., smartphones. Although quite effective, researchers mention some of their disadvantages being the gradually reduced users' immersion when compared to HMD; by contrast, as users are allowed to use their own devices, the level of familiarity is certainly increased, therefore previous training is not needed.

However, Katkuri *et al.* (2019) suggest that in the last decades most of the applications and/or projects developed especially in the tourist framework were not eventually made official and converted to be available in the market. In addition, it is also mentioned that initially there persisted a lack of applications destined to act as tourist guides, as most of them were developed for the tourism industry instead.

The following sections will chronologically present some practical examples of applications that have been developed in the last decades and that have given a fundamental contribution to the evolution of MR technologies in tourism and cultural heritage frameworks.

2.5.1 ARcheoguide project

ARcheoguide (short for Augmented reality-based Cultural heritage On-Site Guide) was an ambitious project that was developed in the early 2000s, and it offered personalised AR tours of archaeological sites. Due to the limited technological evolution of that time, however, it did not use mobile devices, but rather a server system able to manage the flow of data through a series of computers connected to the server via a Wi-Fi network. The device used was therefore an HMD with a geo data tracking system that made it possible to calculate where users were positioned, and which was their orientation. The HMD also allowed to modify users' view and set it as a first-person view.

The first-ever ARcheoguide prototype for testing, demonstration and user evaluation purposes was installed at Greece's Olympia archaeological site, due to "its importance as the birthplace of the ancient Olympic games, its high popularity among visitors, and the fact that it lies mainly in ruins" (Vlahakis *et al.* 2002: 1).

With regard to its practical functions, ARcheoguide is actually a VR application, rather than an AR one, as it displays pre-recorded digital images to the user, to make them match the real environment the user is interacting with. In this way, transformed 3D models are rendered superimposing each live video frame to present the user with an augmented view as displayed in *Figure 2.3*.

Figure 2.2: ARcheovirtual application. Picture (a) represents the ruins of an ancient temple; picture (b) is the digital reconstruction; picture (c) presents all the necessary devices to live the fully immersive experience. (Source: Mesároš 2016)

2.5.2 LifePlus in Pompeii

The LifePlus project was developed in the early 2000s and it proposed an immersive experience set in the ancient Roman city of Pompeii. Papagiannakis *et al.* (2002) offered users the possibility of living in a specific part of the city before its destruction; considering the years during which the project was established, researchers undoubtedly pushed the limits of AR technology. The project was divided into two applications, namely “Arguide” and “AR Life Simulator”: the former was a mobile guide of the surrounding environment that offered audio, image, and text explanations, as well as 3D reconstructions of parts of the city together with architectural information related to the location. By contrast, the latter animated scenes of Roman social life inspired by the events depicted in the mosaics and visitors could observe them walking around the city as if they were themselves part of those.

Taking into consideration its technical features, it used a geolocation tracking system as it happened with ARcheoguide. Furthermore, both outdoor and indoor environments, as well as a natural features tracking system was implemented. The information was processed by a central computer and sent via wireless to a laptop that was carried by the user and included also an HMD and a Webcam. First-person immersion was granted, too.

What has to be noted, however, considering both ARcheoguide and LifePlus is that a tracking system using AR markers could have never been fully employed due to the protected historical areas the projects were conducted in.

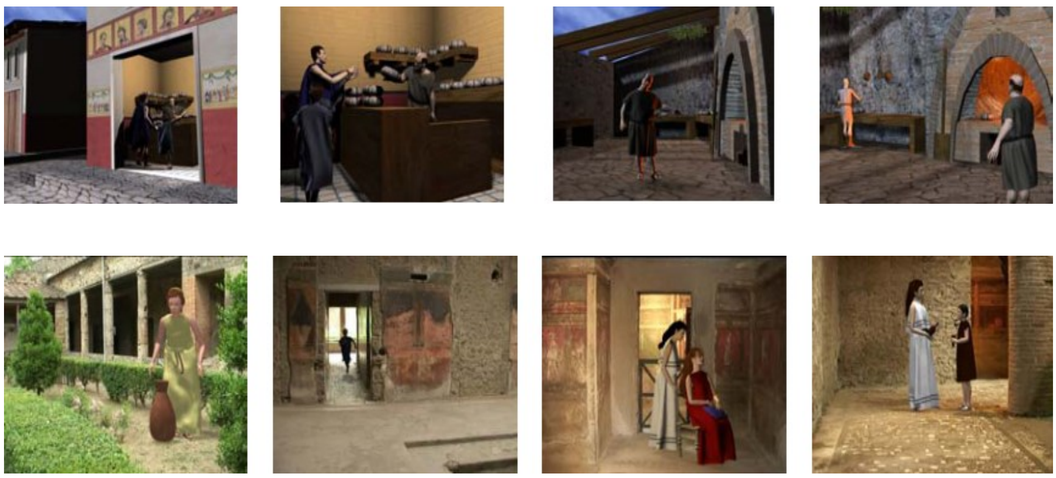


Figure 2.3: Some shots from the LifePlus in Pompeii MR simulation. (Source: Papagiannakis 2002)

As was possible to note given these first two examples, early attempts at MR applications for tourism and cultural heritage involved cutting-edge technology and remarkable financial needs to be realised. Moreover, the devices used to achieve these kinds of immersiveness resulted in heavy sets that tourists had to bring with them throughout the whole duration of the visit. I think that these first two examples are essential to have a wider understanding of the evolution of MR technologies applied to this framework, which allows us to appreciate more recent applications.

2.5.3 Tuscany+

In this regard, extant literature mentions Tuscany+, namely the first AR smartphone app that was release in 2009. Tuscany+ worked as an interactive, real-time guide providing exhaustive facts about a large number of places and attractions limited to the region of Tuscany: framing a certain part of the surrounding area with the smartphone camera, visitors could retrieve live information about it. With regard to its limitations, it only worked on iOS, and it retrieved information only from internet sources in English and Italian languages.

Given all these technological implementations, however, it might be normal to think that the future of tourist professionals might be threatened as they could be completely replaced by technology. It goes without saying that this aspect belongs to those connected to a wider range of ethical issues, as it was already discussed at the end of section 2.4.

2.5.4 The Etruscanning project

The Etruscanning project was presented for the first time in November 2011 during the Archeovirtual exhibition organised by ITABC and V-MusT Network of

Excellence in Paestum, Italy. The project allowed the digital restoration of one of the most famous and historically relevant Etruscan tombs, namely the Regolini-Galassi tomb in Cerveteri: it dates back to around 675-650 BC, and it is the funeral monument of an Etruscan princess and warrior. Due to its private ownership, the virtual reconstruction of the tomb is the only way tourists can actually visit the site, whereas the extraordinary funerary goods are part of the Gregorian Etruscan section of the Vatican Museums. Through its virtual reconstruction both the tomb and its artefacts have been put back together for the first time since their discovery in 1836.

With respect to the virtual acquisition of the site (integrated technologies were employed, e.g., scanner laser, digital photos, photogrammetry), yet researchers had to re-interpret many conflicting literary and iconographic sources to render a 3D model of the tomb alongside its funerary goods perfectly contextualised within its original aspect of the 7th century BC. Interpretative skills were proven to be essential, and as Pietroni and Pagano (2013) stated, such a challenge achieved the final goal of virtual reconstruction, i.e., the cognitive and communicative enhancement of the cultural item translated into a wider and more profound meaning assimilated by each visitor.

Researchers aimed at allowing tourists to perceive a fully emotional experience when visiting the site, and they achieved this through powerful storytelling and sound applications. In the final 3D visualisation, emotional involvement is accomplished with dramatic lights, shadows, and colour correction, as visitors see themselves transported back in the 7th century BC at night-time. Once the exploration of the tomb begins, the voices of both the dead warrior and princess greet the visitors, start talking about their past lives and culture, and also describe the objects that can be found on the site. A particularly smart expedient used in this case is the fact that the two characters do not speak from the past, yet they are aware of the present world; this clearly enhances the level of immersion achieved by visitors. Soundscape and background traditional music played with melodic instruments (i.e., bass flute and alto flute as documented by sources on the Etruscan religious ceremonies) contribute to the immersive environment.

Two main versions of the application have been developed: the first one was released in 2011 and it presented applications common both to an interactive movie and a VR exploration, as visitors could only walk around the environment having a virtual map on the floor as a guide. Some "hotspots" were attached to the map, and once the visitor was standing on them, a pre-determined storytelling sequence begun. The latest version is based on skeleton recognition and on a series of simple gestures to actively interact with the objects in the tomb; the user is therefore left completely free to explore the 3D environment and rotate the point of view in any direction. Lastly, to grant any kind of visitor a pleasing experience, regardless the age and level of pre-existing technical skills, a short tutorial on how to interact inside the 3D space with gestures is given to the user right before the beginning of the experience.

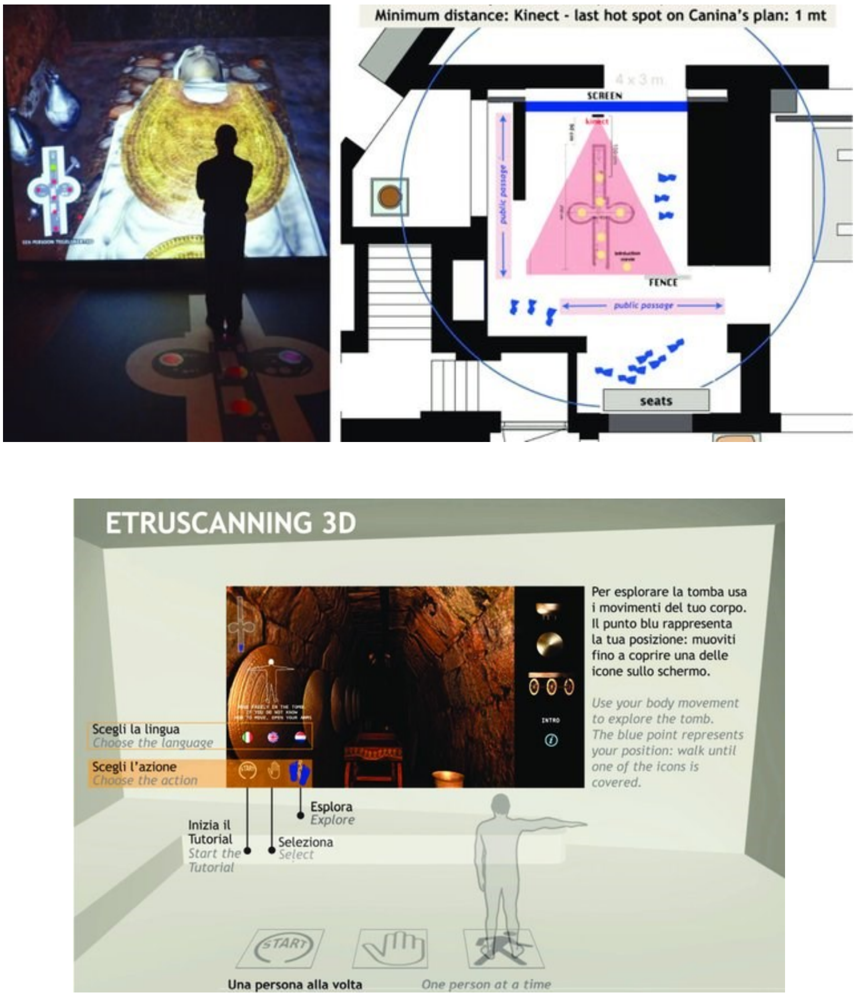


Figure 2.4: The upper image represents the first version of the application with installation and scheme of the application; the lower one is the scheme of interactive place of the second version. (Source: Pietroni et al. 2013)

2.5.5 NosferRAtu project

With regard to the gamification technique discussed in section 2.1.1, the first example of this kind that I present is the NosferRAtu project, an AR smartphone application developed in 2016 by Manusamo&Bzika Art group. Its peculiar name derives from the title of a 1922 silent German expressionist horror film, namely "Nosferatu: A Symphony of Horror", whose plot was inspired by the story of Count Dracula. Given its historical background, the app aims at allowing visitors of the Orava Castle (Slovakia), i.e., the main setting of the aforementioned movie, to experience a completely immersive and interactive guided tour. The game is indeed designed as a quest where players have to explore the castle to collect virtual objects that are hidden in locations where the film was shoot, as well as in historically relevant places; once the object is found, visitors can retrieve some information about it. Moreover, to make the game more challenging, tourists have to complete each step before the virtual vampire that is chasing them actually gets them.

The application only employs the device's camera and inertial and location sensors; the screen of the smartphone acts also as an interaction interface, making this kind of experience accessible to a wide range of people regardless of their age and social status.

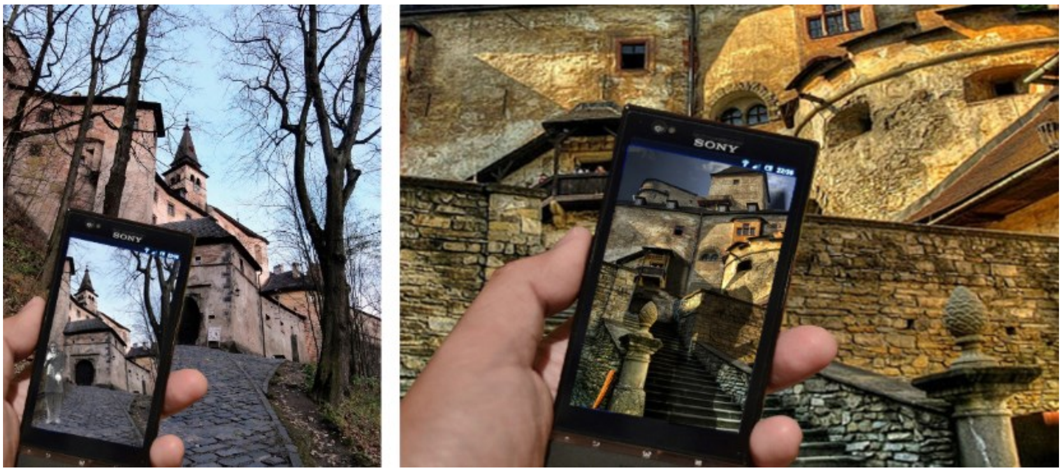


Figure 2.5: NosfeRAtu application. (Source: Mesároš 2016)

2.5.6 TombSeer DCH application

Pedersen *et al.* (2017) carried out a research project on AR applications in museums, with a particular focus on the enhancement of the Egyptian Tomb of Kiribes replica exhibit at the Royal Ontario Museum (ROM) in Canada. TombSeer is the Digital Cultural heritage (DCH) application that engages two primary senses (visual and gestural interaction) and employs a 3D holographic, AR interface aiming at bringing historical artefacts back to life. Researchers assert that the primary motivation behind their project is strictly connected to a previous study that involved possible resources to be implemented in museums for people with disabilities (e.g., blind or low-visioned). In addition, they opted for a tomb as their cultural heritage site of interest, as they believed that "tombs are [...] spaces of unanswered questions, intriguing narratives, and expansive histories that often reach far beyond the tomb walls" (Pedersen *et al.* 2017: 6), therefore they act as perfect starting points for AR applications aiming at revitalising and enhancing a specific site. With regard to its technological functionality, it certainly augments the space with 3D visualisation, allowing viewers to observe a higher amount of information through holographic HMD. Researchers worked alongside the Meta representatives, who also provided the holographic AR headset platform that included a 3D see-through display, depth, and colour camera, 360-degree tracking head tracking, an accelerometer, a gyroscope, a compass, and two built-in microphones. Furthermore, the research team employed a series of interactions for the Meta platform that included (a) staring to select that allowed users to retrieve information about the object that appeared in their field of vision; (b) interacting with 3D objects in an augmented space; (c) pointing at a virtual object to interact;

(d) pinching to scale information large or small; (e) swiping with the hand to move through the various panels of information; (f) pressing virtual buttons to access further information about the artefact.

Lastly, when considering the intrinsic goal of the application, Pedersen *et al.* wanted to achieve full embodiment by tourists, relying on the premise that human participants (i.e., tourists) have to change their role when visiting cultural heritage sites: they need to act mentally and existentially, and they have to be active in the cultural context they are involved in. Therefore, the intent is to avoid the "stand and read" paradigm, to inspire more embodiment and interactivity in museums and galleries.

Figure 2.6: The application ability to interact with virtual objects through gestures (left); developers working to create an augmented overlay for the Tomb of Kitines. (Kayleigh Hindman through Pedersen, 2017)

2.5.7 The Olympic Guides

A further example of gamification is presented by Plecher *et al.* (2019), who designed an AR guide in a museum where ancient statues are reconstructed and lead tourists through the museum visit. The main target of this project is the younger generation, as researchers have noted that visiting museums is not considered a popular activity among young people. They believe that normally it should be the guide's job to captivate visitors' attention and stimulate their imagination through effective storytelling. Therefore, they performed an AR reconstruction of ancient statues of the Olympic gods who also become virtually alive and guide visitors on their way out as the game sees them locked in the museum. Gamification stimulates visitors who are motivated by the story to unlock as much information as possible to solve all the riddles. Tourists could simply interact with the statues detecting them with the camera of their mobile devices (e.g., smartphones or tablets).

With respect to the reconstruction of the statues, software tools such as Unity 3D and Vuforia were used, along with a specific software to build 3D models to allow object tracking. Once the statue was tracked, it was possible to differentiate both the original parts of the statues and the physical reconstructed ones, which had been virtually added beforehand and positioned in the right scale. Whenever it was clear that some of the original statues were coloured, colours were also brought back.

Figure 2.7: Augmented-reality Athena Parthenos; non original virtually reconstructed parts are marked in light blue. (Plecher et al., 2019)

2.5.8 The Pokémon Go phenomenon

This last section will be devoted to the immense possibilities mobile Augmented reality (MAR) games can have in the tourism framework, namely how they can be used as alternative travel guides in the future. More specifically, some findings about the effects of the Pokémon Go app will be illustrated. Extant literature does not give a complete overview in this regard, as it is a relatively new phenomenon and further research with respect to its behavioural and sociological aspects in the tourism application should be considered by future researchers. It is indeed believed that Pokémon Go and similar MAR games could potentially change the way culturally relevant destinations could be marketed in the tourism industry (Aluri, 2017).

The key concept rests on the huge accessibility of mobile devices (i.e., smartphones) among travellers. In addition, increasing importance has been given recently to the phenomenon of Experience Economy that was first conceptualised by Pine and Gilmore in 1998. The two researchers believe in the potential of "intentionally using services as a stage, and goods as props, to engage individual travellers in a way that creates a memorable event" (Pine and Gilmore 1998: 10). Researchers, therefore, believe in the power of gaming as a top entertainment activity that could indeed serve the purpose of enhancing the experiential potential of tourist activities. Although AR mobile apps have been available for smartphones since 2010 without being widely spread among generic users, Pokémon Go completely changed this situation, as it is still regarded as a global and social phenomenon. As its gameplay relies on the smartphone's geolocation, in-game mobility is accessed only through physical travel (Zach *et al.* 2017), which leads gamers to continue walking and exploring new places not only for the sake of the game itself but also for personal interest towards specific landmarks; such a concept is strictly connected to the importance of storytelling applied to tourism, as it creates positive experiences that visitors recall more easily. With regard to its applications in this framework, Aluri (2017) mentions several travel agencies, theme parks and tour companies, especially located in the United States, that have created personalised trips and guided tours around relevant landmarks using Pokémon Go as a platform and receiving much more positive and interesting feedback towards these attractions and destinations. For instance, the Visit Huston agency made it possible for tourists to see major landmarks around the city guided by the Pokémon Go locations where Pokémons could indeed be caught.

With respect to Aluri's study, the target population that was considered consisted of smartphone users in the young adult age range (aged 18-29), as they have proven to be the primary players of a MAR game. They were asked eleven questions regarding their preferences and inventions to use MAR games as travel guides according to their level of use; results showed that most respondents (ca. 77%) would be interested in playing the game with the aim of exploring relevant landmarks as a primary intention. As a further consideration, 73% were positively interested in using other possible customised MAR games as a tour guide if offered by specific businesses, which would inevitably need to customise and personalise PokéStops (i.e., statues, commemorative signs, churches, or other public places) in close proximity to their location to offer value-added services. Customisation would also be effective as it would allow further interaction with the real world while using the app or other MAR services.

CHAPTER 3

Project: A subjective evaluation of cultural heritage 3D models in VR and AR environments

This chapter will present the project that has been developed to give a practical demonstration of the use of AR and VR technologies in the cultural heritage framework through a series of subjective evaluation tests.

I will examine in depth the project that has been conducted to prove the effectiveness of 3D representations in both a VR and AR environment in the cultural heritage framework. Firstly, I will introduce the characteristics participants that took part in the experience; in the following section, will deal with the 3D models that have been shown to the participants in VR and AR environments and that have later been the objects of the subjective evaluation process. Some detailed information on the devices used will be given next, just before focusing on the description of each phase of the experiment itself.

3.1 Introduction

The project involves the subjective evaluation (i.e., an assessment that depends on the opinions, beliefs, and feelings of a person) of 3D models that could be present in museums and cultural heritage sites.

Two main experiments will be conducted: the former sees the visualisation of 3D models using Virtual reality applications (section 3.5), while the latter will employ Augmented reality technology (section 3.6).

3.2 Participants

The participants who took part in the subjective tests were students attending the 3D Augmented reality course offered by the master's degree in ICT at the University of Padua. Students of various nationalities participated to the tests and were all aware of the project they were taking part in, as well as of its aim. With regard to their gender, I positively noticed how there was not a prevalence of one gender in particular, which served as a demonstration that an increasing number of girls have been enrolling in STEM (Science, Technology, Engineering, and Mathematics) courses in the last couple of years. Participation in the experiment was not mandatory; however, students proved to be very excited about it, as for the majority of them it was the first time they used a VR or AR device of any kind. For this reason, the preliminary training part proved to be quite necessary and effective, although some remarks about it were moved by the participants as shown by some of the answers to the questionnaire that they had to fill in once the experience was over. Further details will be provided in the next sections of this chapter.

3.3 Three-dimensional objects

3.3.1 Rendering techniques

When talking about 3D models, it is essential to talk about 3D rendering as well, i.e., the process of generating a three-dimensional image from a real 3D model. Modelling consists in discretely approximating the shape and the surface of both the objects and their surrounding environment. In doing so, the characteristics that have to be taken into account when rendering 3D models are their degree of realism, (i.e., the accuracy of registration in the real environment), the generate sense of depth and volume (which is achieved through stereoscopic vision) as well as the the level of detail. These aspects as a whole have to be evaluated with respect to how they blend together with the surrounding environment, especially when it comes to Augmented reality. For this reason, it is also imperative to take into account how environmental conditions (e.g., background noise, illumination of the room) could affect the 3D model and how it is registered in the real surrounding area. As demonstrated in section 3.6.3 of this chapter, I have asked the participants to answer a questionnaire about their experience emphasising particularly these aspects while filling in the form.

Although complex and detailed mesh models permit representing a 3D object with a high Level-of-Detail (LoD), computational and hardware limitations suggest using more efficient modelling solutions such as voxelisation, point clouds, and mesh simplification.

- Voxelisation is the rendering procedure that involves the use of voxels, i.e., the "3D counterpart(s) to the pixel in 2D" (Open3D, 2018). They are therefore same size volumetric units located in a three-dimensional grid, where they occupy a specific location, and a single colour value is assigned.

- Point Clouds are a set of sparse 3D points sampled over the surface of an object. Each point has various attributes, its own coordinates in the x, y, and z axes and colour values. A distinctive difference between Point Clouds and meshes is that the former lacks any correlation between its points, as they are not linked by any kind of structure. Given the high number of points present in this visualisation, this technique may result in a quite time-consuming processing; for this reason, points are usually converted into polygon meshes or voxels.
- Mesh simplification involves the use of meshes, namely any kind of simple convex polygon defined as a collection of vertices, edges, and faces; in computer graphics, quadrilaterals and triangles are the most used ones. Adjacent polygons define the surface of a 3D object, therefore the wider the surface, the more points (i.e., vertices) will be present. This should lead to a more approximate surface as sensors will find it more difficult to acquire them as a highly performant computational complexity would be required.

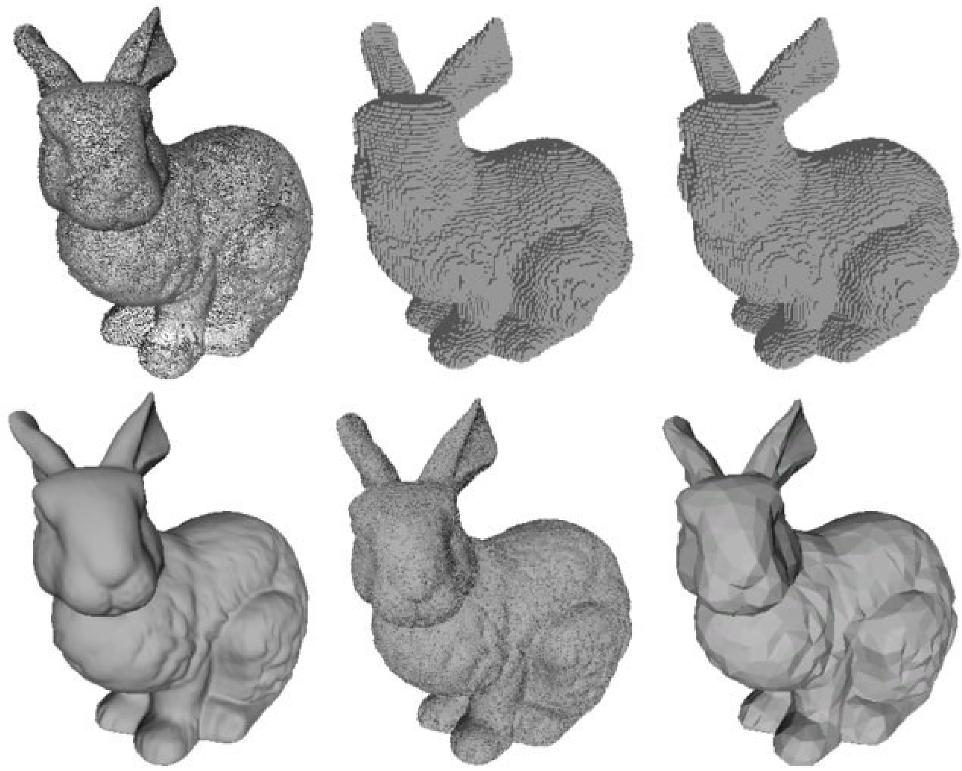


Figure 3.1: Point Cloud, voxel, and mesh representation of the Stanford bunny model. Top: (left) Point Cloud representation; (centre and right) voxel representation from the PC model. Bottom: (left) triangle mesh representation; (centre and right) triangle mesh decimation. (Source: Ylimäki et al. 2015)

Three-dimensional models can be acquired through two main methods, i.e., active and passive acquisition. The former is achieved through the use of specific sensors that enable scanning and collecting three-dimensional data. The latter, however, relies on spatial information algorithms, which means that virtual objects are not scanned from an original source; on the contrary, the virtual copy of the object is created through the recognition of common points among pictures of the real object taken from various angulations. Spatial triangulation is also essential to measure the distance of the objects in the 3D space.

3.3.2 Models used

The experiment that used five 3D virtual mesh models (of which one was only used during the training phase before the real testing began) that had already been used for previous studies conducted by former students under the supervision of professor Milani and his team at the LTTM laboratory of the University of Padua. I initially intended to use models simplified both with mesh and point cloud techniques. However, together with the DEI research team, I eventually decided to opt for mesh simplification only, as it proves to be the most used and effective technique when considering the employment of this kind of technology in the cultural heritage framework.

These models represent both objects and proper environments. From now on they will be referred to with the following denominations:

- *Abbey*: the aerial shot of the Fountain Abbey (Yorkshire, United Kingdom) and its surroundings.
- *Lidded Ewer*: a vase with its respective lid. This artefact belongs to the Smithsonian Museum of Asian Arts (Washington, DC).
- *Mercedes*: a 3D model of a Mercedes Benz GLS 580.
- *Valley*: the aerial shot of a mountain system.
- *Dressing table*: the model used only in the preliminary training phase.

With regard to their acquisition method, two of them (i.e., *Abbey* and *Valley*) were scanned from the original models as they represent proper environments; on the other hand, *Mercedes* and *Lidded Ewer* were virtually generated from scratch. Colours were removed to enhance the geometry of the model, which allowed the participants to focus more on the details of each object; shadows are also present, as they give a more realistic and three-dimensional aspect to the virtual environment and the object itself.

As part of the aim of the experiment is indeed to study how people perceive 3D models in virtual environments, their quality has been decimated using Blender, an open-source 3D graphics software. In this way, the number of faces of each object has been reduced without modifying in any way its shape that remained as close as possible to the original. Five versions with increasingly less quality have therefore been created for each model, with a decimation level of 50%, 20%, 10%, 5% and 1%. However, Mercedes and Abbey's 1% decimation models have not been taken into consideration for the purpose of the test, as such an extreme simplification caused the complete degeneration of the two objects that were therefore unrecognisable (see *Figure 3.2* and *Figure 3.14* for reference). In addition to the five decimated versions, the four original high-quality models have been also included in the final dataset. For each subjective test 22 randomly chosen models with different levels of quality have been used, together with the three versions of the *Dressing table* model, whose three levels of quality (i.e., high quality, medium quality, low quality) were presented following a decreasing order in the training session at the beginning of each test.

Figure 3.2: abbey_001 (Source: Campagnol, 2022)

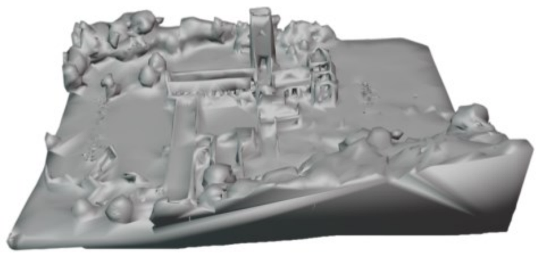


Figure 3.3: abbey_005 (Source: Campagnol, 2022)

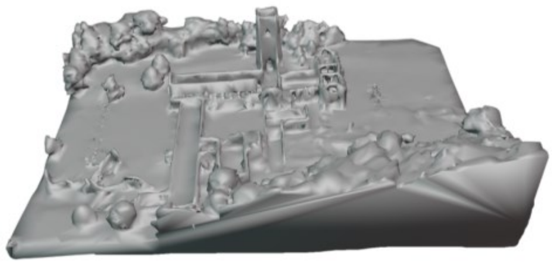


Figure 3.4: abbey_01 (Source: Campagnol, 2022)

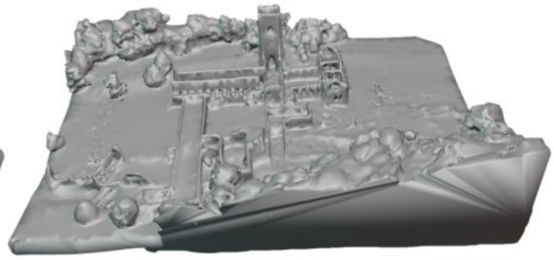


Figure 3.5: abbey_02 (Source: Campagnol, 2022)

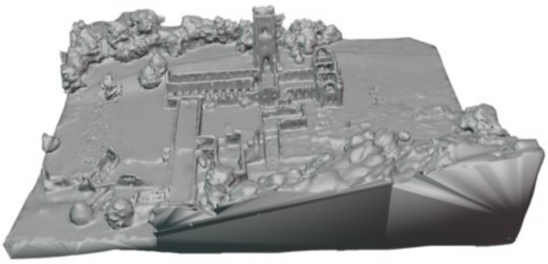


Figure 3.6: abbey_05 (Source: Campagnol, 2022)

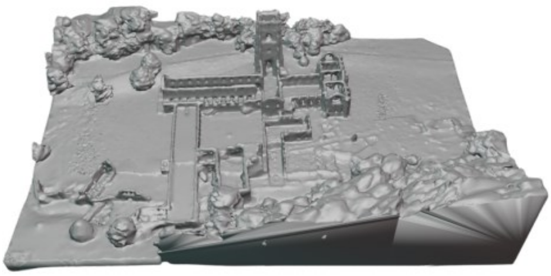


Figure 3.7: abbey_HQ (Source: Campagnol, 2022)

Figure 3.8: liddedewer_001 (Source: Campagnol, 2022)

Figure 3.9: liddedewer_005 (Source: Campagnol, 2022)

Figure 3.10: liddedewer_01 (Source: Campagnol, 2022)

Figure 3.11: liddedewer_02 (Source: Campagnol, 2022)

Figure 3.12: liddedewer_05 (Source: Campagnol, 2022)

Figure 3.13: liddedewer_HQ (Source: Campagnol, 2022)

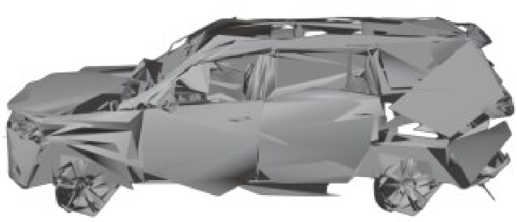


Figure 3.14: mercedes_001 (Source: Campagnol, 2022)

Figure 3.15: mercedes_005 (Source: Campagnol, 2022)

Figure 3.16: mercedes_01 (Source: Campagnol, 2022)

Figure 3.17: mercedes_02 (Source: Campagnol, 2022)

Figure 3.18: mercedes_05 (Source: Campagnol, 2022)

Figure 3.19: mercedes_HQ (Source: Campagnol, 2022)

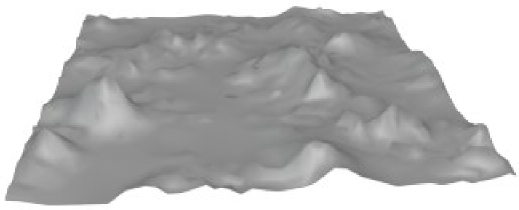


Figure 3.20: valley_001 (Source: Campagnol, 2022)

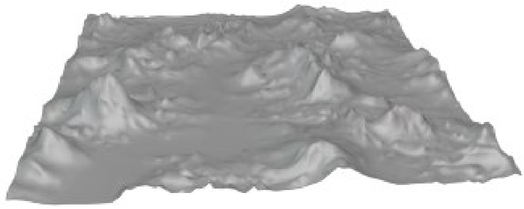


Figure 3.21: valley_002 (Source: Campagnol, 2022)

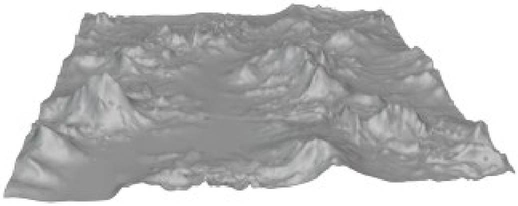


Figure 3.22: valley_01 (Source: Campagnol, 2022)

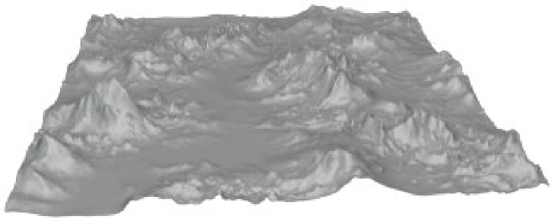


Figure 3.23: valley_02 (Source: Campagnol, 2022)

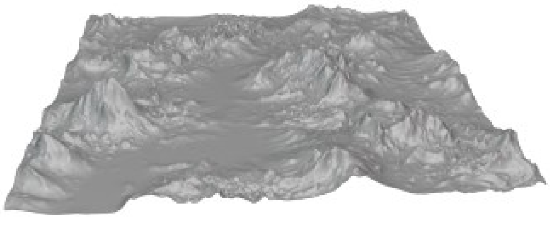


Figure 3.24: valley_05 (Source: Campagnol, 2022)

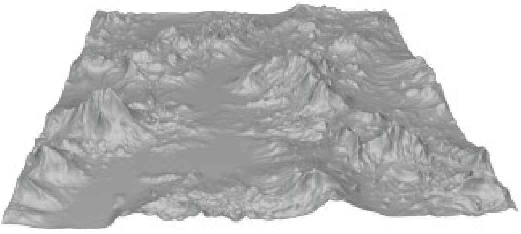


Figure 3.25: valley_HQ (Source: Campagnol, 2022)

3.4 Apparatus

Our subjective tests have been conducted using two different devices: Oculus Quest 2 was used for VR evaluation; on the other hand, the AR experience required the use of Microsoft HoloLens 1.

The following subsections will go into more detail with respect to the specifics of each device.

3.4.1 Oculus Quest 2

Oculus Quest 2 is a wearable HMD produced by Meta, formerly the Facebook company. It is a standalone device, therefore it does not require an external PC to properly function; it is powered by a Qualcomm Snapdragon mobile processor working with an Android-based operating system. What makes Oculus Quest 2 a perfect device for our purpose is that it is supplied with a tracking system of 6 DoF (see section 1.3.2 for reference); it is particularly relevant as it grants impressive freedom of movement, allowing users to observe the 3D models from different angulations, distance and height. Hands tracking (made possible by two controllers included in the box) and gestures are allowed by four cameras on the frontal area of the device; moreover, with regard to the LCD screen, it has a resolution of 1832 x 1920 pixels per eye, and it supports both a 90° field of view, and a refresh rate of 60, 72 (default) and 90 Hz.

With respect to the play area, Meta's official website recommends a room not smaller than 2.7m x 2.7m circa and it should have at least a 2m x 2m of playable area with no obstructions. Users can wear and work with the device both in standing and seated positions.

When talking about its wearability, Oculus Quest 2 presents two adjustable bands (one on the upper part of the head and one adhering to the head circumference) that allow a comfortable fit; moreover, the device has to perfectly adhere to the face, as this prevents from perceiving the surrounding environment as blurred or out of focus. Oculus Quest 2, on the other hand, cannot be worn over glasses, therefore I decided to include a question about this limitation in the questionnaire that I asked participants to fill in at the end of their VR test, to investigate whether and how this affected their overall experience.

Figure 3.26: Oculus Quest 2 and its controllers.

3.4.2 Microsoft HoloLens 1

Microsoft HoloLens 1 is an HMD with a headset structure that allows users to live a full Augmented and Mixed reality experience, although it covers the entirety of the Virtuality-Reality spectrum. Its working mechanism is based on the optical see-through principle, i.e., users see both the real environment and the virtual objects through a mirror that is partially transmissive and partially reflective. In this way, a sufficient amount of light from the real environment passes through the mirror, and, simultaneously, the virtual image is overlaid onto the real world.

This device runs the Windows Holographic operative system, which is based on Windows 10 and it provides users with a performant and secure platform to work with; it also mounts a custom-built Microsoft Holographic Processing Unit (HPU). With respect to further specifications, it presents a set of see-through holographic lenses that allow the AR environment (i.e., mixed holograms and physical environment photos and videos) to perfectly blend in the real world. Moreover, its Field of View (FoV) reaches 35° horizontally and 18° vertically and it supports 6 DoF. Microsoft HoloLens 1 presents a wide range of sensors, more specifically it has one inertial measurement unit (it includes accelerometers, gyroscopes, and magnetometers to report the orientation of the body), four environment understanding cameras, one depth camera, one 2MP photo / HD video camera, four microphones and one ambient light sensor. In addition, to guarantee a completely immersive experience, Microsoft HoloLens is provided with a pair of small, red 3D audio speakers positioned near the users' ears; they do not completely cancel out surrounding sounds, nevertheless, they allow users to experience their virtual environment without headphones.

With respect to the interface, HPU allows users to employ natural voice and gaze commands, as well as hand gestures to interact with the virtual scene.

- Voice commands make it possible for the device to transform users' words into configurable actions or operations in the operative system.
- Gaze commands are referred only to head tracking, which brings focus to the virtual object users are looking at to make them select it; gaze commands do not support eye tracking.
- Gestures are another user interface in HoloLens. The most commonly used ones are the "air tap" gesture, quite similar to clicking an imaginary mouse, that allows selecting an element; the "bloom" gesture makes it possible to access the shell and consists in opening a hand with its fingers spreading and the palm facing up; it is also possible to "pin" windows or menus within the environment, but they can also be "carried" by users as they move around the scene.

Lastly, what is to be noted is that, unlike Oculus Quest 2, the device can be worn over eyeglasses.

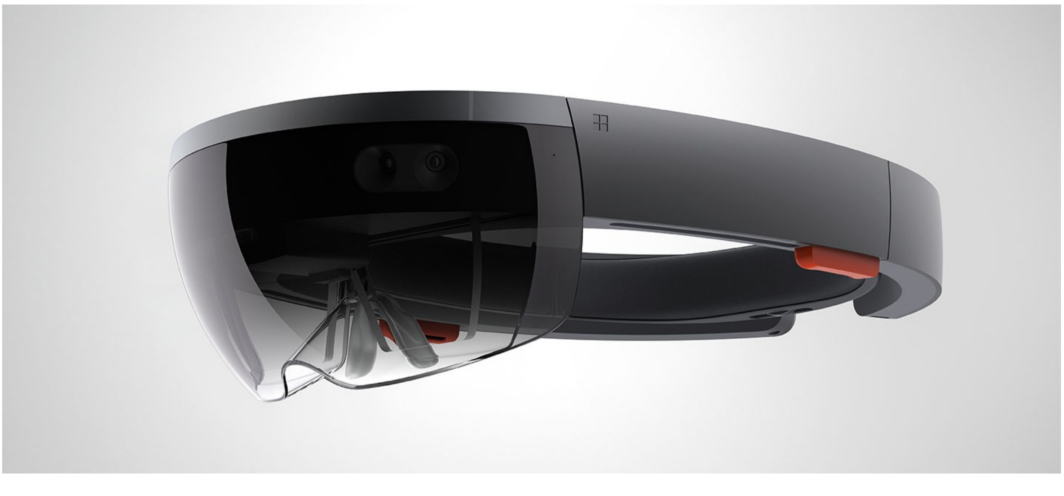


Figure 3.27: Microsoft HoloLens 1.

3.5 VR Project phases

I conducted the VR test during the last week of October 2022, to give students enough time to approach the subject of interest, which was particularly in line with the topics dealt with in the MSc course of 3D Augmented reality that they started attending at the beginning of the 2022/2023 academic year. 35 students took part in this test overall.

Both the VR and the AR projects followed the pre-existing models implemented by a former student during his work on his bachelor's thesis (Campagnol 2022).

3.5.1 Room preparation

The first part of the test took place in a specific laboratory room of the Department of Information Engineering that perfectly served our purpose. As it is possible to note in *Figure 3.28*, the majority of the room is occupied by an elevated blue platform (i.e., the play area) that is surrounded by a green net; this protects the testers while being immersed in the virtual environment, especially when they use the Oculus Quest 2 visor. For this reason, before the beginning of each testing session, the device asked to track the borders of the play area; it also notified when unknown obstacles were detected there.

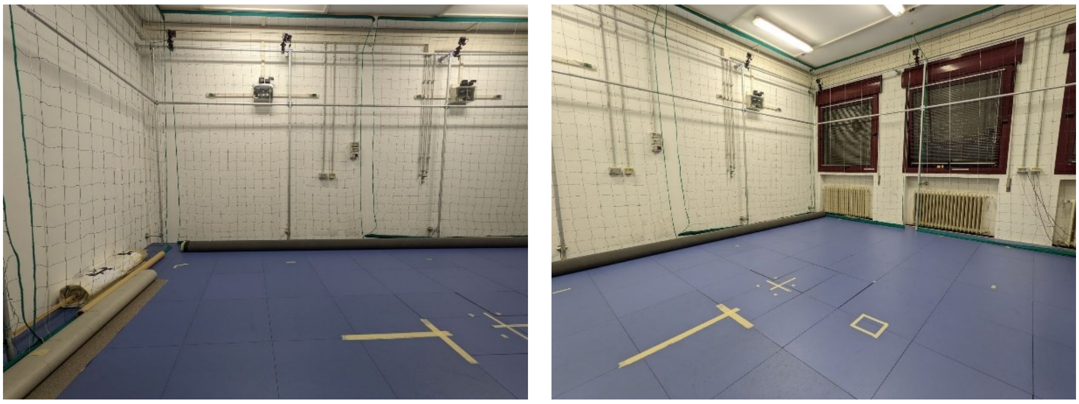


Figure 3.28: Play area of the laboratory room at the Department of Information Engineering.

3.5.2 Project execution

I then proceeded in gathering the students all together and organising them into timeslots, calculating 20 minutes circa per person, although the required time needed per session proved to go from 10 to 15 minutes.

Before each test, I made sure each student could wear the visor comfortably and completely adherent to their face to avoid out-of-focus vision of the virtual environment. I then explained the details of the project which consisted of two main phases, a training and a testing phase. The former involved the visualisation of the same model (i.e., the Dressing table of *Figure 3.29*) repeated three times with three different degrees of quality; in this way, participants could get accustomed to the level of detail they would have later seen in the proper testing phase and how they should have rated it.

Figure 3.29: The high-quality dressing table training model used in the tests. (Source: Campagnol 2022)

After each visualisation, participants were required to express a quality evaluation of the model they had just seen expressing a value ranging on a scale from 1-worst quality to 5-best quality (see *Figure 3.30* for reference). This range is part of the Mean Opinion Score (MOS) evaluation method, which is commonly employed in subjective tests. It serves as a way to evaluate the quality of an object once each participant is subjected to a specific stimulus. MOS evaluation can be conducted after a single stimulus (SS) or a double stimulus (DS): the former requires each participant to evaluate a single item immediately after having seen it; the latter presents a pair of items at the same time, the original high-quality one and its degraded-quality equivalent. For the purpose of the experiment, I opted for the SS MOS evaluation technique.

Each visualisation lasted approximately 20 seconds.

Figure 3.30: Evaluation panel. (Source: Campagnol 2022)

In this first part of the test, the training models were presented following a decreasing quality order; the data collected during this first phase, however, were not considered for the sake of the experiment.

Once the training phase was over, the testing phase began. At this point, participants were asked to evaluate the quality of a series of different 3D models (see section 3.3.2 for reference). This time, the objects appeared at random degrees of quality, therefore participants had to evaluate each one only following their impressions giving a proper subjective evaluation. No limitations in movements were given, students could freely walk around the model within the play area and get closer to it. The following pictures were taken during the tests and show how students moved around the room.

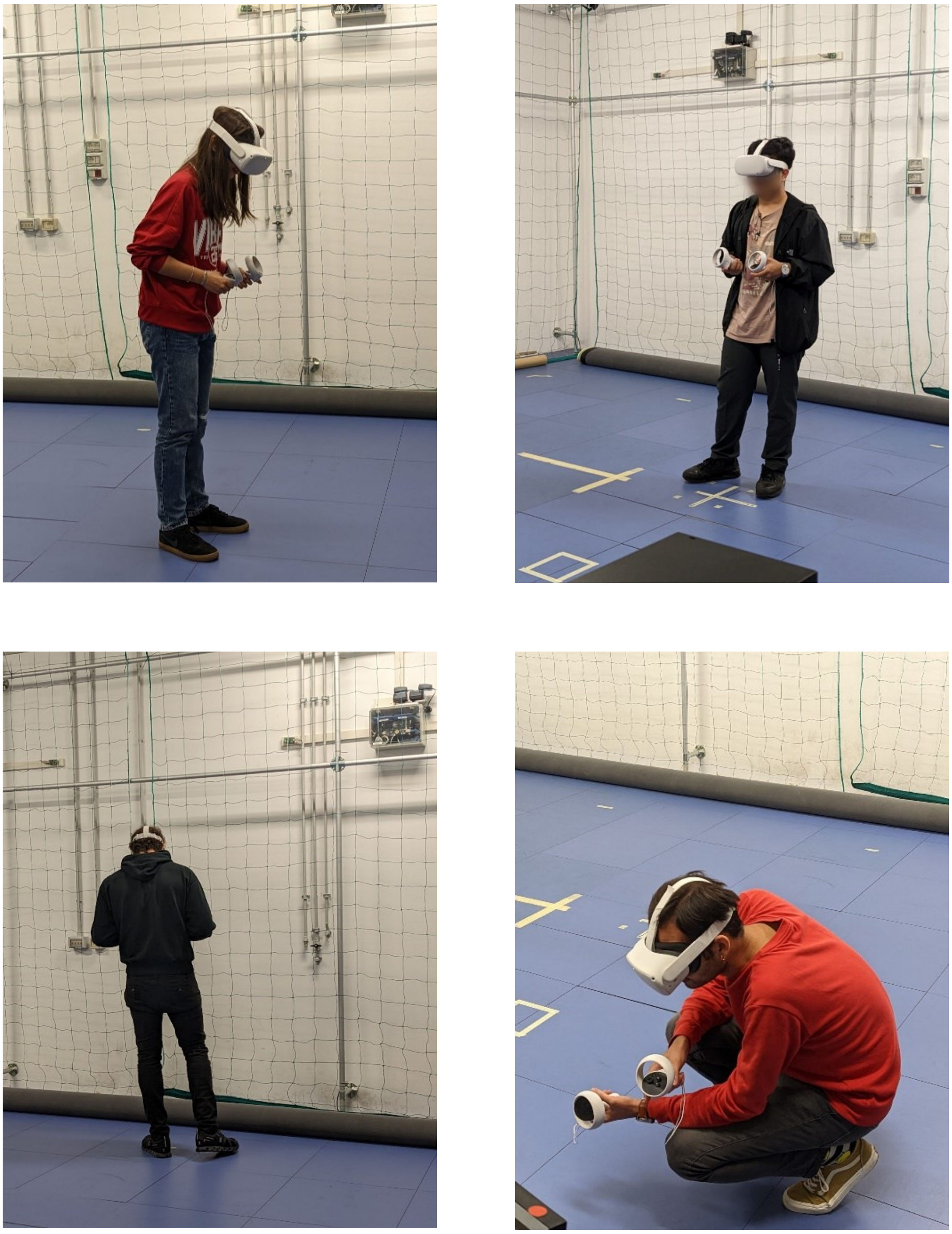
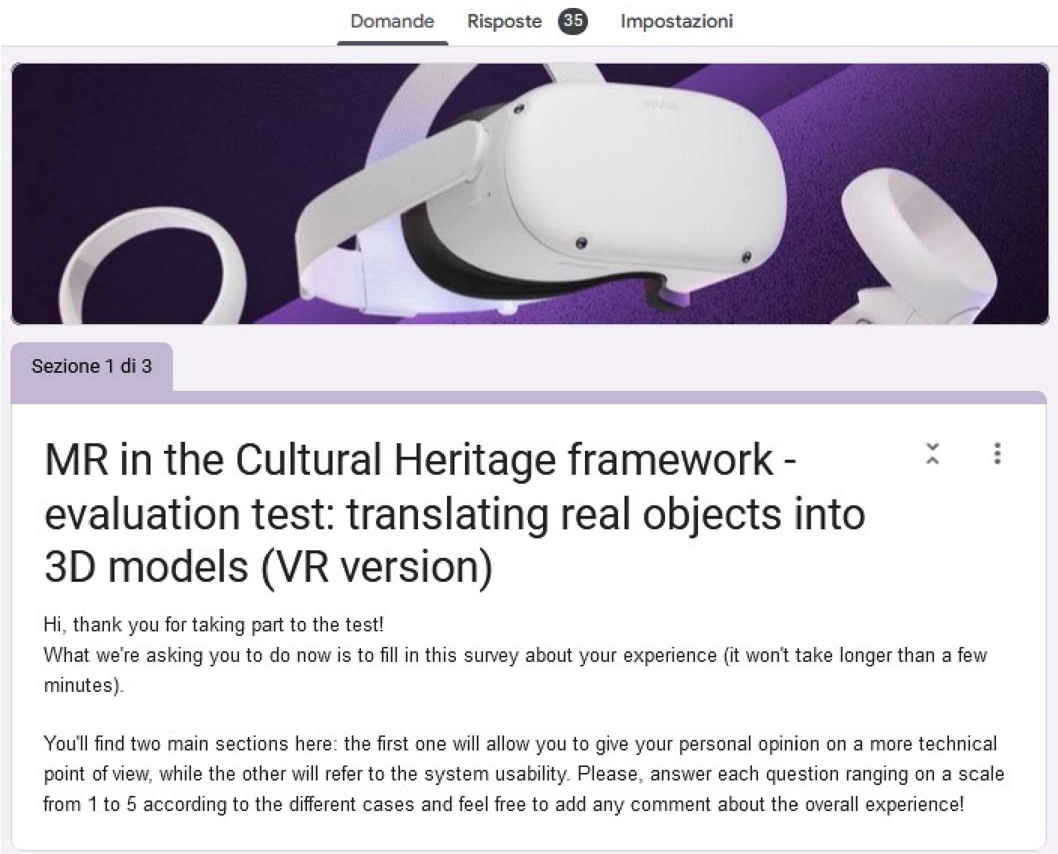


Figure 3.31: Some pictures of the participants during the VR test.

3.5.3 Final questionnaire

At the end of the immersive experience, students were asked to fill in a questionnaire (APPENDIX A) about their overall evaluation experience. The form titled "MR in the Cultural heritage framework - evaluation test: translating real objects into 3D models (VR version)" was created using Google Forms, which I opted for as it is an easy-to-use platform that could allow immediate sharing with the participants.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Sezione 1 di 3

MR in the Cultural Heritage framework - evaluation test: translating real objects into 3D models (VR version)

Hi, thank you for taking part to the test!
What we're asking you to do now is to fill in this survey about your experience (it won't take longer than a few minutes).

You'll find two main sections here: the first one will allow you to give your personal opinion on a more technical point of view, while the other will refer to the system usability. Please, answer each question ranging on a scale from 1 to 5 according to the different cases and feel free to add any comment about the overall experience!

Figure 3.32: Introduction to the VR questionnaire.

The questionnaire consists of 14 questions divided into two main sections: the former allows participants to give their personal opinions about the test from a more technical point of view, while the latter refers to the system's usability considering the possible applications in museums or other cultural heritage sites. In this case, too, the majority of the questions could be answered by giving a score ranging from 1 to 5; this kind of evaluation is based on the Likert scale, that is to say, a unidimensional scale used by researchers to collect attitudes and opinions of a group of respondents. Usually, the Likert scale requires answers that make participants express their agreement or disagreement level, assuming that the intensity of the experience is linear, going from a completely positive to a completely negative opinion. As it applies to our case, a 5-point Likert scale is adequate when it is needed to gather subjective opinions about a topic including neutral answers (i.e., a 3-point answer). With respect to the questionnaire, however, the value of the two extreme answers varied from question to question; for instance, for question 1 (Do you already have some kind of knowledge with respect to this technology?) the answer could range from 1-beginner to 5-expert. On the other hand, question 5 (How would you rate the overall quality of the object in the 3D model?) could be answered from 1-very high to 5-very low.

The questions that have been chosen for the survey were formulated bearing in mind the intended users of the system taken into analysis, their tasks, and the characteristics of the environment they would be in during the test. As reported by Brooke (1995) in its System Usability Scale overview, effectiveness, efficiency, and satisfaction are the most relevant usability measures; I have therefore drafted the form trying to elaborate questions following this thought.

I will now consider some of the questions of the survey and analyse them with respect to these considerations.

- Question 1 (Do you already have some kind of knowledge with respect to this kind of technology) has been chosen in that it is fundamental to understand the level of pre-existent knowledge users have before a specific experience.
- Question 2 (How well is the 3D model registered in the real environment?), question 3 (How would you rate the deepness representation achieved through stereoscopic vision?), question 4 (How would you rate the detailed level of the 3D model?), and question 5 (How would you rate the overall quality of the object in the 3D model?) were added as a way to analyse the 3D models and how they were perceived with respect to the technology they were immersed in. Consequently, specific kinds of aspects concerning general environmental conditions that could possibly affect the way the model is perceived were not included in this questionnaire, as this kind of problem would be related only to an experience in Augmented reality. Further details about this will be given in section 3.6.3 where a more detailed analysis of the AR questionnaire (APPENDIX B) will be provided.
- Question 8 (Do you believe the device used (i.e., Oculus Quest 2) was appropriate for this kind of purpose?), question 9 (Do you think that people with no practical background with regard to this technology would autonomously use it in museums?), question 10 (How difficult do you think they would find it?), and question 11 (Do you think some sort of preliminary

training is needed before the immersive experience?) are all part of the "System Usability" section and have been selected as I wanted to focus notably on the way such a kind of experience would be perceived by common users without any kind of previous experience neither on this field nor on this kind of technology.

- Questions 13 (Do you wear glasses?) and 14 (If so, comment whether you found any difficulties) have been added once I became aware, right before the beginning of the first tests, that although immersed in a virtual world, eye diseases could have brought to some kind of bias in the evaluation of 3D objects. This is all due to the fact that, as previously mentioned in section 3.4.1, Oculus Quest 2 cannot be worn over glasses. The answers to these questions lead to interesting results that will be reported in the following chapter.

3.6 AR project phases

The AR test was conducted in the first week of November 2022, and 17 students in total took part in the experiment. The majority of them also participated in the previous VR experience.

In this case, too, the mesh models that have been used were the ones presented in section 3.3.2. However, they had to be adapted to the Augmented reality environment they were inserted in, and consequently to the device employed for this new session of tests.

3.6.1 Room preparation

The room used for the AR test was the same laboratory of *Figure 3.28*. However, contrary to the VR experience, in this case there was no need to track the borders of the room, as participants could see the real environment surrounding them due to the nature of the Augmented reality. Indeed, the experience could have taken place in any other room or space with adequate illumination conditions and with little background noise.

3.6.2 Project execution

As it already happened in the VR test, this time too I organised the participants in time slots, estimating circa 15 minutes per person. However, in this case time was managed differently during each session, as students could move autonomously in the interface. In this way, they could look at the 3D model for as long as they wanted and had to press a specific button to move on to the evaluation panel. This inevitably led to tests that lasted way less than 15 minutes, while other participants required more time both to evaluate the object, and to become familiar with the visor and its functioning.

Before the beginning of each session, I accurately explained each student what the project was about (although most of them already took part in the VR test), but most importantly I took some time to train them on the functioning of the device. Contrary to the Oculus Quest 2 experience, participants did not use controllers to move the pointer and select items. In fact, they needed to move their head slightly to visualise the pointer (a red circle) and move it on the item that they wanted to select. They could opt for either the "air tap" hand gesture (see section 3.4.2 for reference) or voice commands to select and proceed with the test. Specifically, once the clickable item was pointed, a disappearing bubble with the suggestion of the correct voice command appeared next to the button. As in this case participants could choose freely which selecting method to opt for during their sessions, I decided to include a specific question about this in the final questionnaire (Question 12, APPENDIX B).

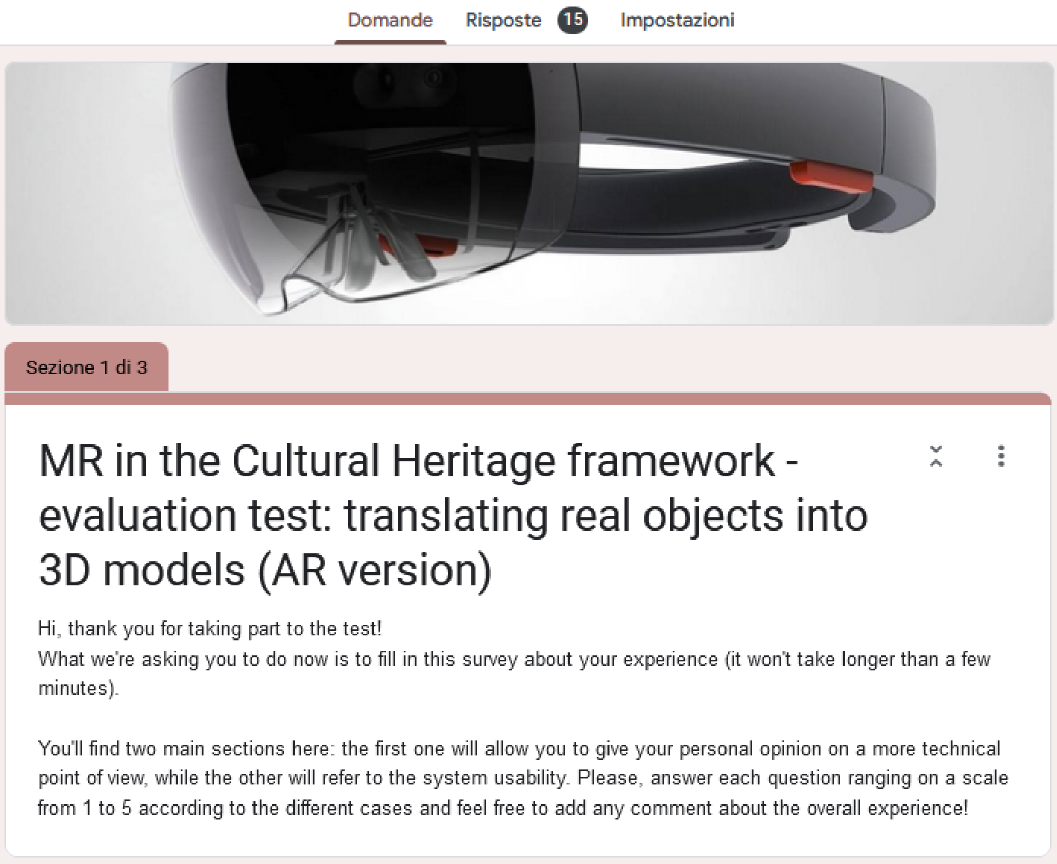
Otherwise, the evaluation test was followed the exact same procedure of the VR test, thus he main changes in the experience regarded mostly the way the 3D models were visualised in the AR environment and the level of usability of the device.

Figure 3.33: Some shots of the AR experience, i.e., the starting panel with the red pointer selecting the play button (top); a random version of the Lidded Ewer model (middle); the evaluation panel (bottom).

Figure 3.34: Some pictures of the participants during the AR test.

3.6.3 Final questionnaire

As happened at the end of the VR experience, participants were asked to fill in a final questionnaire (APPENDIX B) about their overall impressions titled “MR in the Cultural heritage framework - evaluation test: translating real objects into 3D models (AR version)”. It consists of 17 questions divided into the same two sections already mentioned in the VR version of the questionnaire. Likert-scale answers have been used in this case, too, aside from questions 12 and 17 which require short answers only.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Sezione 1 di 3

MR in the Cultural Heritage framework - evaluation test: translating real objects into 3D models (AR version)

Hi, thank you for taking part to the test!
What we're asking you to do now is to fill in this survey about your experience (it won't take longer than a few minutes).

You'll find two main sections here: the first one will allow you to give your personal opinion on a more technical point of view, while the other will refer to the system usability. Please, answer each question ranging on a scale from 1 to 5 according to the different cases and feel free to add any comment about the overall experience!

Figure 3.35: Introduction to the AR questionnaire.

As was already mentioned in section 3.5.3, most of the questions are common to both questionnaires. Nonetheless, some additions had to be made with respect to this form, as environmental conditions of the laboratory in which the test was conducted could affect the overall perception of the superimposed 3D models. Questions 7 (How would you rate the environmental lighting conditions with respect to the AR model?) and 8 (How much do you believe the environmental conditions (e.g., background noise, illumination of the room) have affected your general experience?) have been added with this purpose.

The System Usability questions that have been asked specifically in this form are all referred to how participants felt in wearing the visor.

- Question 10 (How would you rate its wearability?) refers to how comfortable participants felt in wearing Microsoft HoloLens 1. I have added this question in particular, as I am aware of the considerable weight of the visor, hence I wanted to investigate whether this actually affected the overall experience.
- Question 11 (How would you rate the width of the field of view?) refers to a further limit of the device, i.e., its restricted FoV. I therefore wanted to investigate whether participants could be affected by this in the evaluation progress.
- Question 12 (Have you used voice commands or gestures?) aimed at understanding which kind of command participants found themselves more comfortable in using. Question 13 (How would you rate the use of gestures?) is strictly connected to the previous question, as I wanted to examine how the use of gestures to select items was evaluated by participants. I do indeed believe this way of interacting with the device's interface might not be completely user-friendly, which is why voice commands can be used, too.

Lastly, no questions in the System Usability section about the possible difficulties that may arise for people with eye problems have been added, as the Microsoft HoloLens 1 visor can be comfortably worn with glasses still on.

CHAPTER 4
Data Analysis

This final chapter will present all the data resulting from the tests conducted as discussed in Chapter 3.

4.1 VR subjective test

The data analysed in this section are all referred to the VR subjective test of section 3.5. Once all the participants' sessions were over, I imported the data from the device directly into our computers as .csv files. They were organised into two main file typologies:

- "eval" files contained all relevant information about each session of the test, namely the UserID, the DisplayID (each model shown during a specific session), the Rating, the StartTime and the EndTime (how much time each user spent in rating each model in terms of milliseconds); 35 total files have been downloaded from the visor, namely a file per participant.
- "log" files, on the other hand, registered the Timestamp, the Position of the visor, the head Rotation, the number of FPS, the UserID, and the DisplayID for each model and its relative quality that has been shown in all the test sessions.

For the sake of the analysis conducted in this Chapter, I have taken into consideration only the data from "eval" files, most specifically the DisplayID and the Rating; our primary aim is indeed to verify how each model and its respective lower-quality equivalent have been rated by the participants.

Lastly, to allow a better comprehension of the figures in the next sections, each model and its relative quality are going to be named as follows:

- *abbey_005* (5% quality), *abbely_01* (10% quality), *abbey_02* (20% quality), *abbey_05* (50% quality), *abbey_HQ* (original model);
- *liddedewer_001* (1% quality), *liddedewer_005* (5% quality), *liddedewer_01* (10% quality), *liddedewer_02* (20% quality), *liddedewer_05* (50% quality), *liddedewer_HQ* (original model);
- *mercedes_005* (5% quality), *mercedes_01* (10% quality), *mercedes_02* (20% quality), *mercedes_05* (50% quality), *mercedes_HQ* (original quality);
- *valley_001* (1% quality), *valley_005* (5% quality), *valley_01* (10% quality), *valley_02* (20% quality), *valley_05* (50% quality), *valley_HQ* (original quality).

4.1.1 Abbey

Figure 4.1 shows that the Abbey mesh and its variations in quality have been valued following the increasing quality order. However, what has to be noted is the relatively scarce difference between the lowest and the highest quality score; it is in fact possible to notice that *abbey_005* has a mean score of 2.26, while *abbey_HQ* scored 3.64 (only slightly more than a point of difference). With regard to the other variations, they are just a few decimals distant from one another, which makes it possible to assume that not much difference has been perceived by participants.

This is, however, a new outcome with respect to previous studies on the same set of models (i.e., Campagnol, 2022), as *abbey_HQ*, although its low score, has been rightfully recognised as the highest quality model of the set; on the contrary, Campagnol's results proved *abbey_05* to be regarded to as the most realistic model.

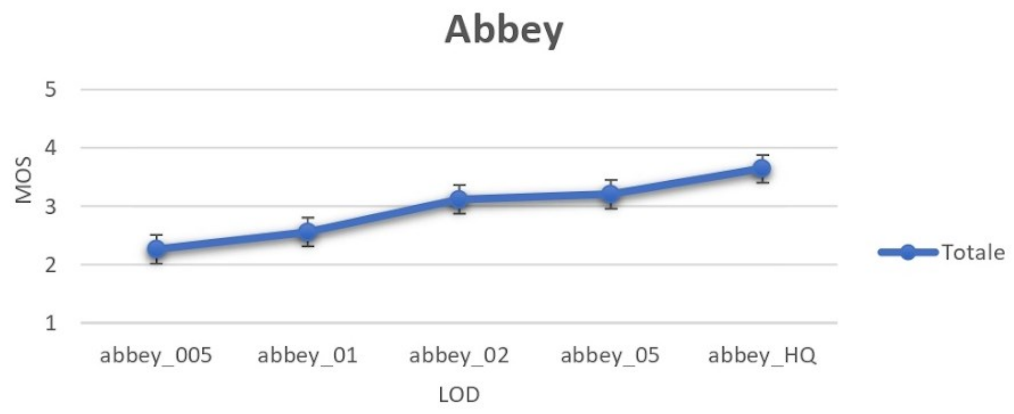

Figure 4.1: MOS values for the Abbey model (VR).

	abbey_005	abbey_01	abbey_02	abbey_05	abbey_HQ
MOS	2.26	2.55	3.11	3.20	3.65

Table 4.1: MOS values for the Abbey mode (VR).

4.1.2 Lidded Ewer

The Lidded Ewer model and its variations did not give any kind of unexpected result, as the MOS follows a relatively smooth increasing trend. What is quite noticeable here is the considerable distance between *liddedewer_001* and *liddedewer_005*: this might be due to the fact that the original model is quite elaborate and full of details, therefore a heavy simplification may lead to a distorted version that is completely different from the highest-quality one.

Figure 4.2: MOS values for the Lidded Ewer model (VR).

	lidded_001	lidded_005	lidded_01	lidded_02	lidded_05	lidded_HQ
MOS	1.60	2.74	3.12	3.60	4.26	4.5

Table 4.2: MOS values for the Lidded Ewer model (VR).

4.1.3 Mercedes

Yet again, no unexpected outcomes are to be found in the evaluation of Mercedes models. As it happened with the lowest-quality variation of the Lidded Ewer, it is possible to notice quite an interesting increase of positive evaluation from *mercedes_005* and *mercedes_01*. The trend proceeds almost linearly for the other models, with the peak being reached by the original highest-quality model that has received an evaluation of 4. This may lead to suppose that, although the quality of the 3D model was indeed the highest one, participants did not evaluate it with the highest mark as they did not know whether an even more detailed variation could eventually exist.

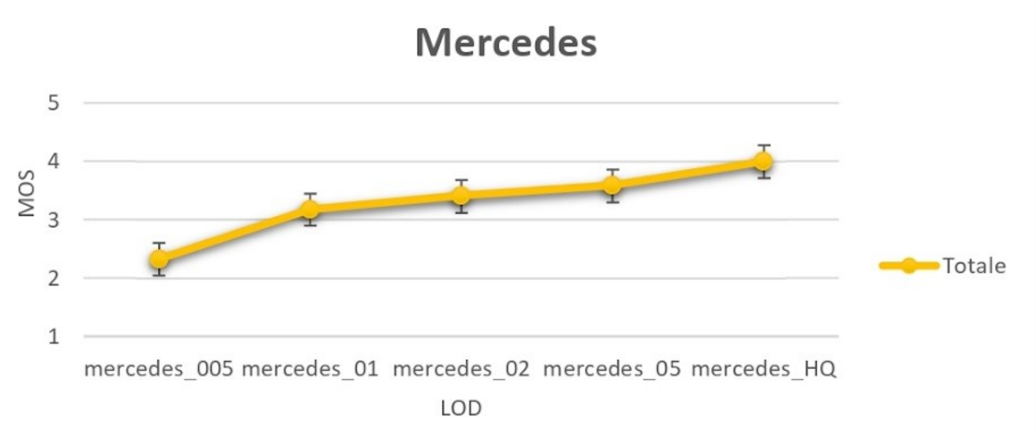

Figure 4.3: MOS values for the Mercedes model (VR).

	mercedes_005	mercedes_01	mercedes_02	mercedes_05	mercedes_HQ
MOS	2.32	3.18	3.42	3.58	4

Table 4.3: MOS values for the Mercedes model (VR).

4.1.4 Valley

With respect to Valley, the tendency shows quite peculiar results: although a quite increasing trend in the evaluation of each variation, with a distinct difference in quality between *valley_001* and *valley_005*, the highest-quality model proves to be evaluated with a lower level of detail with respect to *valley_05*. When comparing these results to the aforementioned previous studies by Campagnol (2022), I could note a similar phenomenon with regard to *valley_05* and *valley_HQ*, which leads to the conclusion that these two variations could be easily interchangeable; when used in a specific field of application, it would therefore be more effective to show users the degraded-quality model, as it would affect less the memory of the device and its resources in general.

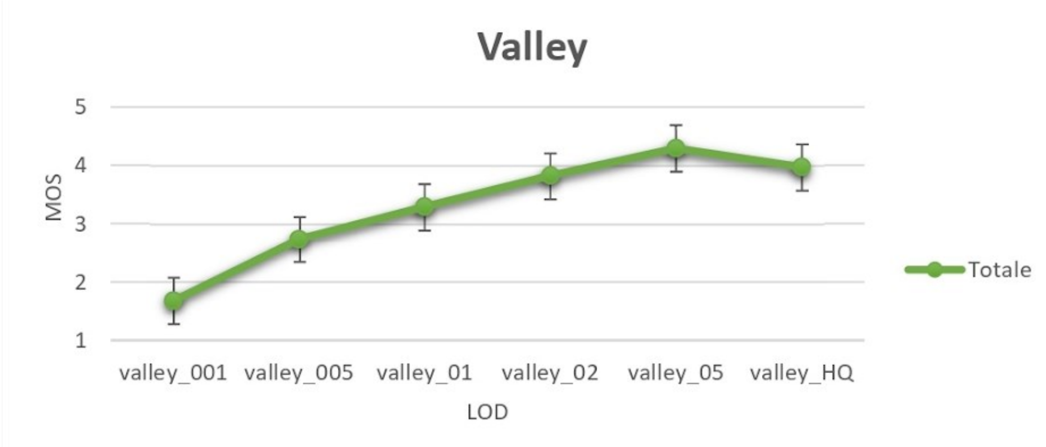

Figure 4.4: MOS values for the Valley model (VR).

	valley_001	valley_005	valley_01	valley_02	valley_05	valley_HQ
MOS	1.68	2.74	3.30	3.82	4.30	3.97

Table 4.4: MOS values for the Valley model (VR).

4.1.5 Overview and some preliminary conclusions

Figure 4.5 shows an overview of all the models and their respective variations as one, which allows to draw some interesting conclusions with respect to the subjective tests that have been taken into consideration so far.

Firstly, what has to be noted is the evident difference registered between the lowest-quality models and their subsequent variations; this difference is particularly relevant for Lidded Ewer, Mercedes and Valley models. On the contrary, Abbey presents a higher difference in evaluation between *abbey_01* and *abbey_02*. A further noticeable variance has to be observed between *liddedewer_02* and *liddedewer_05*; in addition, given that the Lidded Ewer high-quality model has registered the highest rate (i.e., a 4.5 MOS) with respect to the other original counterparts, I believe that this result has to do with the nature of the object taken into account. As I have already observed before, Lidded Ewer is the model with the highest number of details with respect to the others analysed in the experiment, meaning that a sharper quality has to be perceived more distinctly, especially in this case.

Lastly, some further remarks have to be made with respect to the Abbey and Valley models, as they do not represent objects but rather landscapes. Indeed, this might be the reason behind some of the findings: on one hand, Abbey's highest-quality model has reached the lowest MOS with respect to the others (i.e., 3.65), possibly due to the fact that it might be hard to scan all the essential details of a landscape to make it as similar as possible to reality; in addition, students might have assigned lower marks overall as they did not know for sure that the model they were looking at was actually the highest-quality one. On the other hand, Valley's models have scored high marks in general, although *valley_HQ* was not recognised as the best-quality one. Again, it might be assumed that this result is strictly connected to the nature of the model itself, a landscape, that is nothing but a mere approximation of the real-life reference.

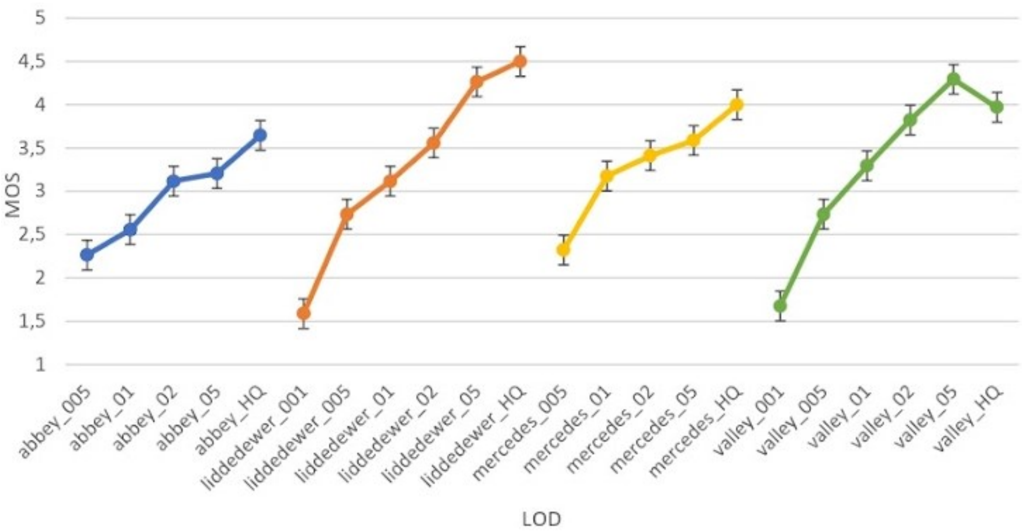

Figure 4.5: MOS values of all the models (VR).

4.2 VR questionnaire

This section will analyse in detail the answers to the questionnaire that I asked the participants to the subjective tests to fill in once their experience was over (APPENDIX A). Detailed information on the questionnaire and how it was created can be found in section 3.5.3.

4.2.1 Preliminary knowledge about VR technology

Figure 4.6 shows the answers to the first question of the survey. As it is possible to notice, most of the students who took part in the tests had little or no previous knowledge on the VR technology employed. Only 14.3% of the students already had an acceptable familiarity with the device, as some of them owned one, or knew someone who owned it and had the possibility to try it beforehand a consistent number of times. None of the students, however, considered themselves experts in this field.

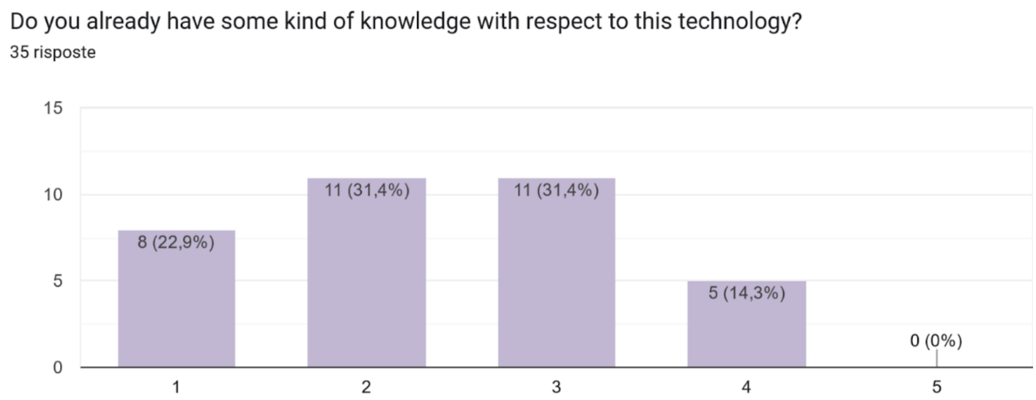

Figure 4.6: Answers to Question 1 (APPENDIX A)

We can consider these first results as quite effective for the purpose of the experiment, as I wanted to investigate primarily how non-expert people could interface with VR technologies. Further questions in this regard will be analysed in the following sections, although it is important to point out this consideration now, still bearing in mind that the participants were students of the master's degree course in ICT, which makes them people already with a more technology-oriented mindset.

4.2.2 Technical evaluation section

With respect to the questions about the models and how they interfaced with the virtual environment, I can consider that the overall evaluation has led to positive results.

- Each model was adequately registered in the virtual environment for 54.3% of the students, and only for 6 students the objects had high registration standards in the virtual environment; however, 28.6% of the participants gave a neutral answer to this parameter, possibly due to some visualisation problems found in students with some sort of eye disease.

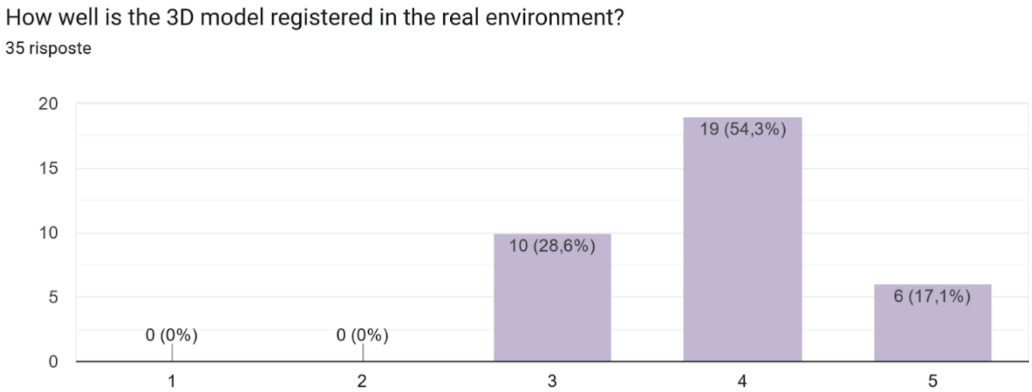

Figure 4.7: Answers to Question 2 (APPENDIX A)

- Deepness representation achieved through stereoscopic vision was rated positively by 60% of the participants; in any case, here too some exceptions can be noticed, as only 2 students gave a low rating to this aspect. As only a small percentage of the participants gave this evaluation, I do not consider it relevantly important for the sake of the experiment.

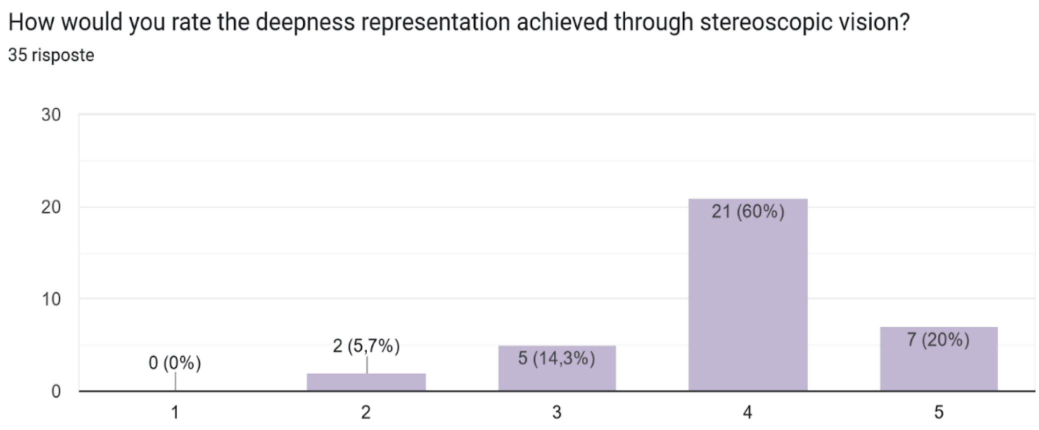

Figure 4.8: Answers to Question 3 (APPENDIX A)

- The LOD and the overall quality of the 3D models have been positively evaluated, with the former reaching the maximum rate by 40% of the participants; the latter (*Figure 4.9*), however, sees a consistent majority of the students rating the quality with 4 points (43%), with some isolated cases of bad quality evaluation.

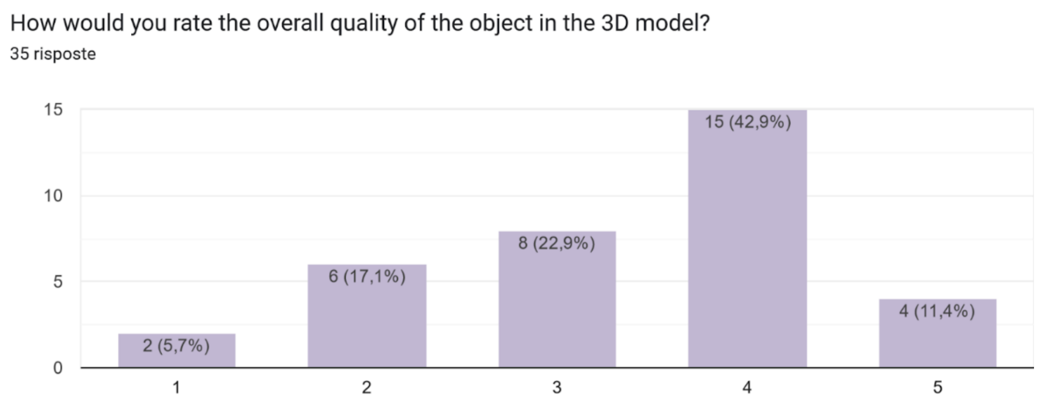

Figure 4.9: Answers to Question 5 (APPENDIX A)

- The experience was considered highly immersive by the participants, with 4 and 5 points given respectively by 34.3% and 28.6% of the students; some lower ratings are found here, too, although still quite irrelevant with respect to the overall trend. Some of the reasons behind these results might be found in the answers to the question presented below.
- The last question of this section asked participants about possible suggestions for the implementation of the model. Students answered proposing various alternatives: many participants suggested the use of colours in the models to make them as realistic as possible; in addition, the lack of colours made the experience less immersive for some, as they could clearly understand they were looking at prototypes because the only way they could define the level of reality of each model was through its shadows. In this respect, some suggested adding further illumination to get a higher level of depth. Other comments to increase the immersiveness of the experience regarded a more isolating audio system to completely cancel external sounds, as well as a more interactive application, through which users can directly touch, rotate and move objects to have a complete view and therefore to give a more effective evaluation. Other ideas were related to the use of a contrasting background colour instead of the white walls of the virtual room where the experience took place, as it would allow making some details of the model analysed more noticeable. Additional remarks were made also with respect to the evaluation process itself, as some assumed the scores they gave to specific objects could be heavily influenced by the previous models that they saw; for this reason, one of the participants

suggested the possibility to show more than one object (e.g., at least the previous one, just to remember more clearly what it looked like) during each evaluation stage. One of the participants also said that it would be useful to have a visible countdown to know exactly how much time he/she has left to look at the model before assigning his/her score. Lastly, participants reported some problems in the visualisation of the models without their glasses on; moreover, once the experience was over, they would feel their eyes tired and heavy, although the time use limit of approximately 20 minutes was never exceeded.

4.2.3 System usability section

The figures in this last section refer to questions that wanted to investigate the level of usability of this kind of technology specifically in the cultural heritage framework and taking into consideration users without any kind of preparation in this field. In this case, too, results prove to be quite optimistic.

- We first asked students to evaluate the device used for the tests (i.e., Oculus Quest 2), and the majority (57.1%) answered positively to this question.

- The second question of this section wanted to investigate whether common users would autonomously use this kind of technology, with "autonomously" meaning without the need to ask experts to help them in understanding how it worked. Results proved that 43% of the participants believe that no kind of difficulty would be found in this regard; nonetheless, 28.6% gave 3 points to this question, implying that some users would rather ask for help, as the functioning mechanism would not be so straightforward.

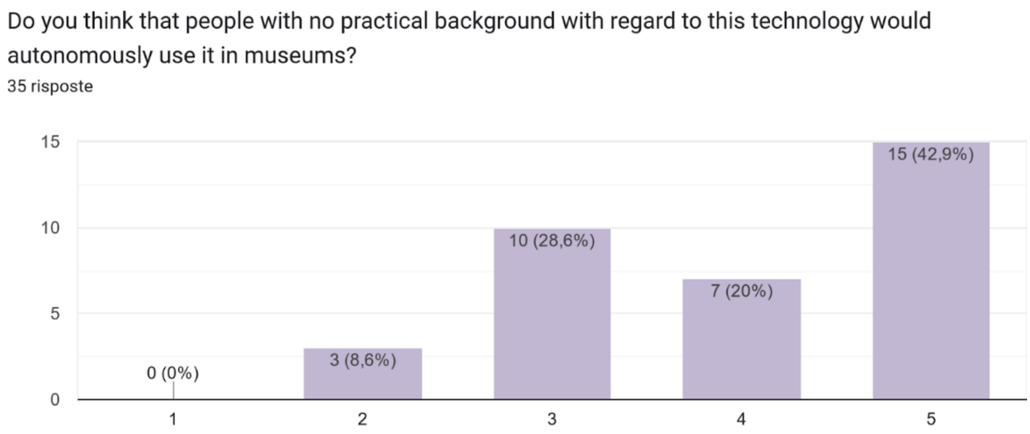

Figure 4.10: Answers to Question 9 (APPENDIX A)

- As for the following question, only 11.4% of the participants believe that common users would find such a technology difficult to use, with the vast majority believing that no difficulty at all would be manifested.

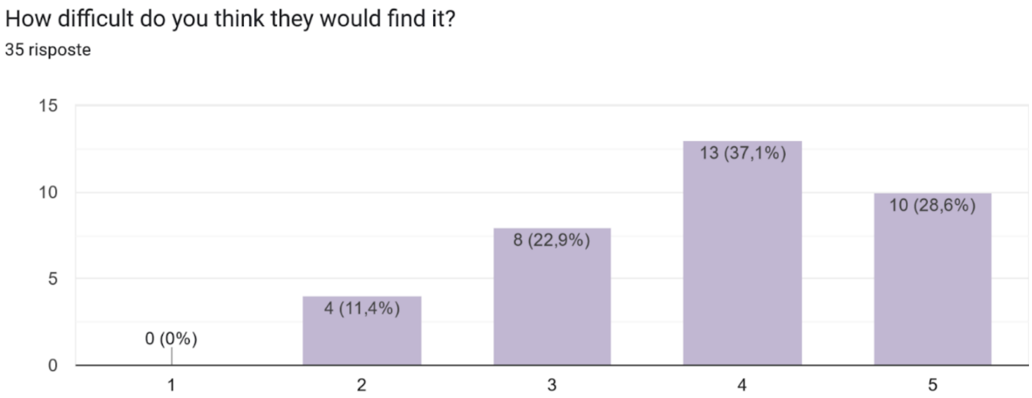

Figure 4.11: Answers to Question 10 (APPENDIX A)

- When asked whether some sort of preliminary training would be needed before the immersive experience, only 4 students gave one point (i.e., necessary) to this question, while the highest number of participants believe that no training at all would make the experience enjoyable, nevertheless.

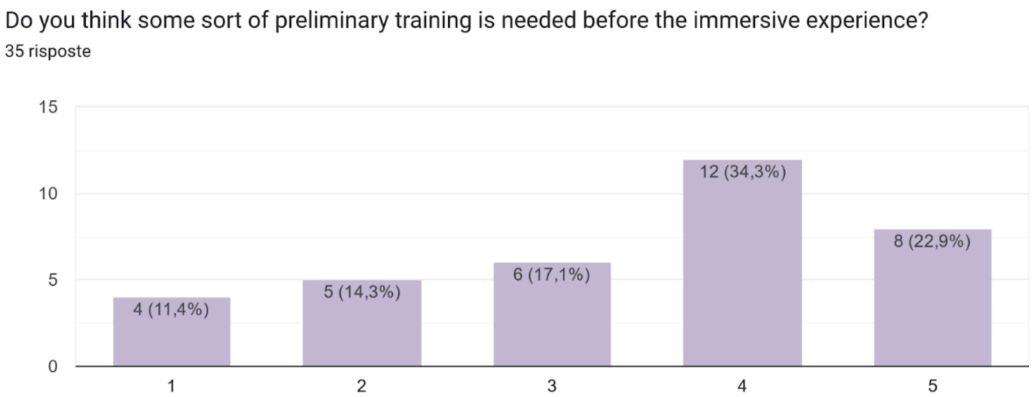

Figure 4.12: Answers to Question 11 (APPENDIX A)

- At this point, I asked participants to give some final suggestions, in particular with respect to the system usability. Some remarks overlap with the ones reported in the previous section; nevertheless, further comments are related to the need for a longer training session before the beginning of the actual testing phase, with more models to be analysed to better understand the quality level and apply the correct evaluation in the testing phase. In this regard, one participant suggested adding any kind of realistic reference (e.g., a video or a picture) to the real object, rather than a computer graphics equivalent. Some students also found it difficult to use the controllers during the test, as it did not come naturally to them to press specific buttons even after the short explanation provided before the beginning of the immersive experience. For this reason, some believe it would be easier to use the device only with hand gestures, as it happens with Microsoft HoloLens indeed. Furthermore, one participant proposed the idea of implementing the virtual environment with an audio description of the scene and the object portrayed; this suggestion could certainly be taken into account when considering users with severe eye impairments that could not be solved in any way by the visor. However, this would certainly lead to a different kind of immersive experience that could not be as effective for all kinds of users.
- One last question was then reserved for participants who usually wear glasses, to further investigate whether they had any particular problem according to their needs, as they had to take them off to use the device. Only 3 participants out of the 15 people who took part in the investigation and

also wore glasses did not find any difficulty; 1 participant usually wears contact lenses, therefore he was not affected by any problem; 1 participant believes he/she perceived the environment as blurry only because he/she did not manage to stabilise the device and make it adherent to his/her face. With respect to the remaining participants, the most common problem they reported was that they could not read the words properly as they looked too blurry; they also found it difficult to grade similar levels of accuracy as they could not manage to properly recognise the main differences from a model to another. For this reason, they had to focus a lot on the object and stress their eyes, which resulted eventually in eye fatigue at the end of the test.

4.3 AR subjective tests

The data presented here are all referred to the subjective tests analysed in section 3.6. In this case there was no need to import the data from the visor into our computers, as Microsoft HoloLens 1 is able to connect to its same Wi-Fi network. Consequently, the “eval” and “log” .csv files (see section 4.1 for reference) are saved in real time in the visor application on the computer once every session is concluded, which only left us the task to locally download them.

In addition, as was the case for the VR tests, I have only taken into consideration the DisplayID and the Rating data from the “eval” files. The other set of information acquired during these subjective evaluations will serve as useful resources for future studies on head tracking and response time rate that will be conducted by the LTTM laboratory of the Department of Information Engineering.

The names of the models and their relative quality variations are still named as those considered in the VR experience as listed in section 4.1.

In the following sections I will present the data collected for each model and its variations.

4.3.1 Abbey

Figure 4.13 presents particularly interesting results. Participants have not recognised the difference in quality between *abbey_005* and *abbey_01*, as the former has been given a slightly higher MOS with respect to the latter. The only increasing trend that it is possible to note here is registered between *abbey_01* and *abbey_02*, which is the variation that has also reached the higher score (i.e., 3.17). Lastly, both *abbey_05* and *abbey_HQ* have not been rated positively, with the highest-quality variation rated with a MOS of 2.92, which is lower than the one received by *abbey_05*. These results are definitely less positive that the equivalents in the VR experience. This might be due to two main factors: the former is the nature of the model (i.e., a landscape), which does not help in enhancing the perception of its LoD; the latter refers to the complexity of higher-quality models. They do indeed present a high number of details, which leads to the need to visualise more surfaces. In this way, the computational abilities of the visor are stressed to their limit, which results in a less smooth visualisation of the models, hence the HQ objects are mistaken for lower-quality ones. This explanation can be applied also to the data that will be presented in the next sections.

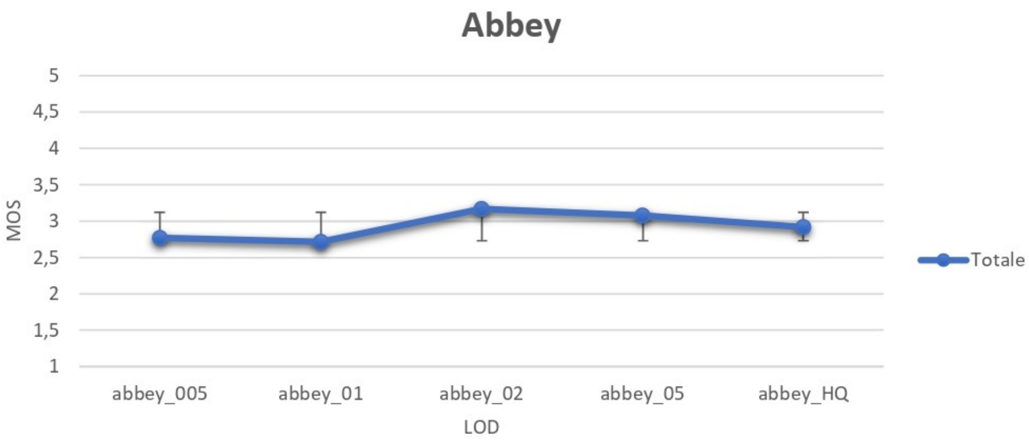

Figure 4.13: MOS values for the Abbey model (AR).

	abbey_005	abbey_01	abbey_02	abbey_05	abbey_HQ
MOS	2.77	2.71	3.17	3.08	2.92

Table 4.5: MOS values for the abbey model (AR).

4.3.2 Lidded Ewer

With regard to the Lidded Ewer models, some unexpected results are presented again: the lowest-quality variation has been rated more positively when compared to *liddedewer_005*; nonetheless, even lower scores have been attributed to *liddedewer_02* and *liddedewer_05*, whose MOS are respectively 2.44 and 2.64. However, contrary to the Abbey model, in this case the HQ variation has been recognised as such, with its score being the highest registered (i.e., 3.22). This is a completely different trend when comparing these data with their VR equivalents (section 4.1.2), as in that case the trend followed a linear increase in the scores.

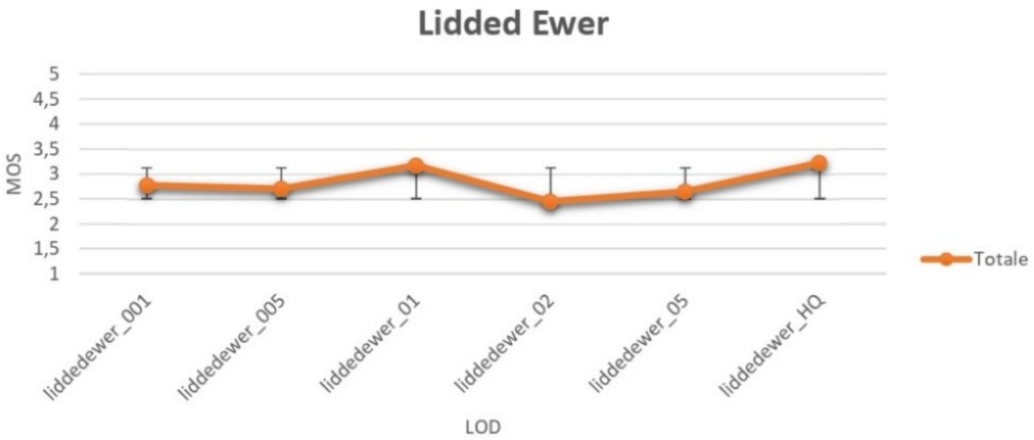

Figure 4.14: MOS values for the Lidded Ewer model (AR).

	lidded_001	lidded_005	lidded_01	lidded_02	lidded_05	lidded_HQ
MOS	2.77	2.70	3.17	2.44	2.64	3.22

Table 4.6: MOS values for the Lidded Ewer model (AR).

4.3.3 Mercedes

The results of the evaluation of the Mercedes models are quite peculiar, as from *Figure 4.15* it is clearly possible to notice that *mercedes_005* and *mercedes_01* have registered the same score, i.e., 3.54, which is also the highest MOS for this set of models. An evident fall in the evaluation of *mercedes_02* can be clearly seen, and it is followed by a slight improvement with *mercedes_05* reaching a score of 3. Lastly, the highest-quality model has been given the lowest grade of this set, with a MOS of 2.44. In this case, too, results are extremely different if compared with the VR experience evaluations of the same set of quality variations. One of the reasons that might explain this set of peculiar data is that participants might have thought that the artefacts[3] that can be seen in the first two levels of detail were indeed intentional (e.g., to represent a car after a car crash). The decreasing trend in the other variations is due to the complexity of the model as it happened in the other set of objects. However, the DEI research unit will conduct further tests in the future to check whether our suppositions are correct.

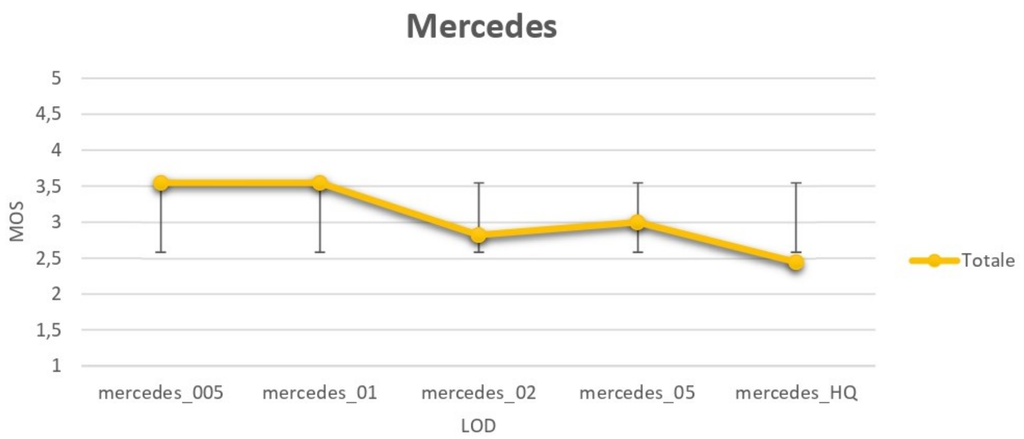

Figure 4.15: MOS values for the Mercedes model (AR).

	mercedes_005	mercedes_01	mercedes_02	mercedes_05	mercedes_HQ
MOS	3.54	3.54	2.81	3	2.44

Table 4.7: MOS values for the Mercedes model (AR).

[3] Here intended as noisy details in the resulted by the mesh simplification of the object, and not as ancient objects in museums.

4.3.4 Valley

The mean opinion scores of the Valley set of models do confirm again the same trend that has been noticed in the previous sections. Lower-quality variations have registered similar scores with respect to the previous models, with *valley_005* reaching the same MOS of the equivalent model in the Mercedes set, i.e., 3.54. In this case, too, it is possible to highlight the decreasing trend starting from *valley_005* leading to the lowest score of the set of models, i.e., 2.70 registered by *valley_02*. From this point on, it is possible to observe a slight increase in the grades attributed to *valley_05* and *valley_HQ*, which do however stay below the ones of the previous quality variations, with *valley_HQ* reaching a score of only 3.07.

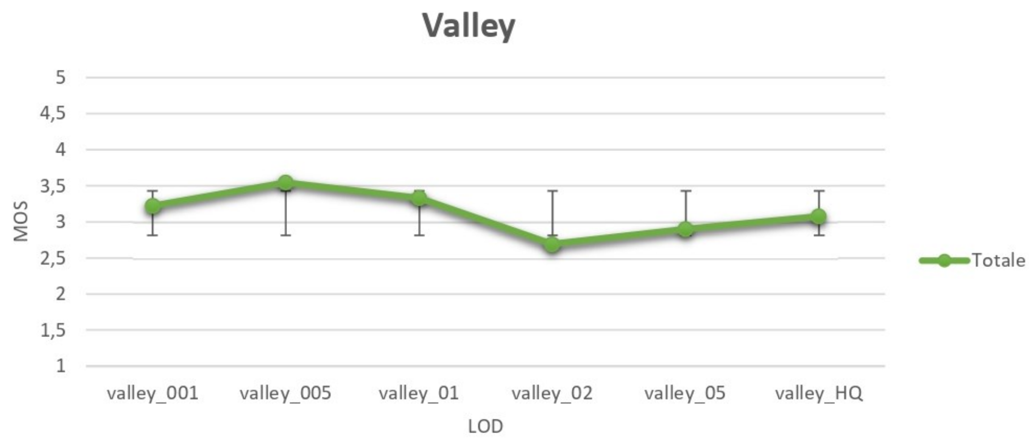

Figure 4.16: MOS values for the Valley model (AR).

	valley_001	valley_005	valley_01	valley_02	valley_05	valley_HQ
MOS	3.22	3.54	3.33	2.69	2.90	3.07

Table 4.8: MOS values for the Valley model (AR).

4.3.5 Overview and some preliminary conclusions

Figure 4.17 serves now as a way to summarise all the data that have been analysed in the previous sections, as well as to get a more general overview that could help us draw some important preliminary conclusions with respect to the AR subjective evaluation tests.

What strikes attention most, considering previous analysis, is that the lowest MOS level that has been registered in half of the cases is the one belonging to the 20% quality degradation (i.e., *liddedewer_02*, *valley_02*). This does not apply only to *abbey_02*, which, on the contrary, has the highest MOS of the Abbey set, and to *mercedes_02*, whose lowest score is the one registered by *mercedes_HQ* indeed. Moreover, Abbey's models are the ones where peaks of high and low evaluations do not differ that much, the higher value being 3.17 (*abbey_02*), and the lower 2.71 (*abbey_01*), with a difference only of 0.46 points. Comparing this data with the other models, it is possible to see that:

- Lidded Ewer's extreme evaluations go from 3.22 points (*liddedewer_HQ*) to 2.44 (*liddedewer_02*), the difference in this case being 0.78 points;
- Mercedes highest scores are the ones of both m*ercedes_005* and *mercedes*_01 (i.e., 3.54), while the lowest is 2.44 (*mercedes_HQ*) leading to a difference of 1.1 points;
- Valley models go from 3.54 points (*valley_005*) to 2.69 points (*valley_02*), hence a difference of 0.85 points is registered in this case.

From these considerations, it is noticeable that the highest value registered in general is 3.54 indeed, which would not be usually considered as a bad score, but it is certainly relevant here, also in respect to the highest value registered in the VR experiment, i.e., 4.5 by *liddedewer_HQ*.

A further consideration in this regard should focus on the kind of models taken into account. As I have noted in section 4.1.5, Abbey and Valley do not represent objects, but rather landscapes, therefore their general LoD is more difficult to evaluate with respect to other models as Lidded Ewer and Mercedes. In the VR experience, data confirmed this assumption, with Abbey's higher-quality model having reached the lowest MOS (i.e., 3.65) with respect to the others, and *liddedewer_05* receiving a higher score than *liddedewer_HQ* (this being the only case of this kind in that experiment tests). On the contrary, in the AR experiment the fact that the two models do indeed represent landscapes is not representative of any kind of distinctive result. All the models present, indeed, a series of peculiarities that, I believe, are not linked to the object themselves, but rather to the kind of device used and its limitations. The following question will also try to investigate in this regard.

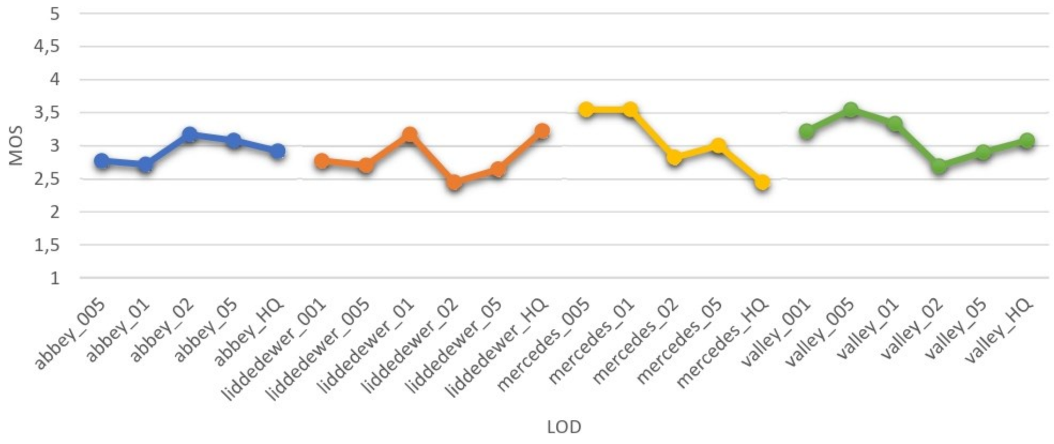

Figure 4.17: MOS values of all the models (AR).

4.4 AR questionnaire

This section aims at analysing the answers that participants gave to the questionnaire (APPENDIX B) I asked them to fill in once their experience was over. Further information about the form and how it was created can be read in section 3.6.3.

4.4.1 Preliminary knowledge about AR technology

Figure 4.18 shows how participants answered to the first question that whether they had some preliminary kind of knowledge with respect to the kind of technology involved in this case, i.e., AR. As it is possible to notice, the majority of participants had little or no knowledge in this respect. Only two participants (12.6%) were already particularly familiar with it.

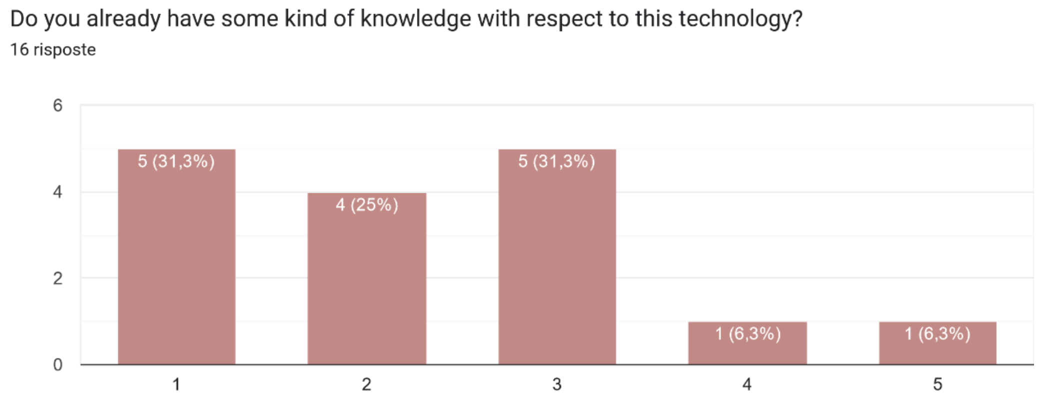

Figure 4.18: Answers to Question 1 (APPENDIX B)

As was the case with the VR experiments, it proves to be essential to have a large number of participants who are not accustomed to the kind of technology they will deal with, as it somehow resembles the same conditions that could occur in various kinds of field of applications that involve the participation of people who have possibly never made use of any AR devices.

4.4.2 Technical evaluation section

With respect to the answers to this set of questions, it is possible to affirm that they lead to overall positive results, although some major problems have been observed in the limited FoV and stabilisation provided by the device. This might have led to some bias in the evaluation of the models, indeed.

- Each model has been perceived as adequately registered in the environment by 43.8% of the participants, with 37.5% giving a neutral answer to this question. Only one person believes that the system would need further implementation in this regard.

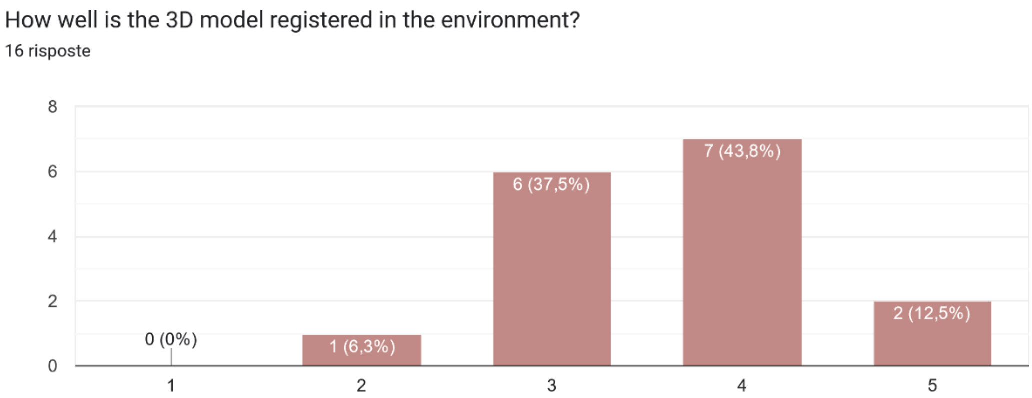

Figure 4.19: Answers to Question 2 (APPENDIX B)

- Deepness representation, too, has been valued as highly acceptable, with only 37.5% of the participants giving a neutral answer to the question. Two people (12.5%) graded the deepness representation as perfect.

- Very positive results have been registered both by the LoD of the 3D models and their overall quality. 25% of the participants rated the LoD as perfect, and 56.3% gave it the second highest score. With respect to the overall quality of the object (*Figure 4.20*), a 6 people (37.5%) defined it as normal, while the majority (again the 56.3%) rated it very positively.

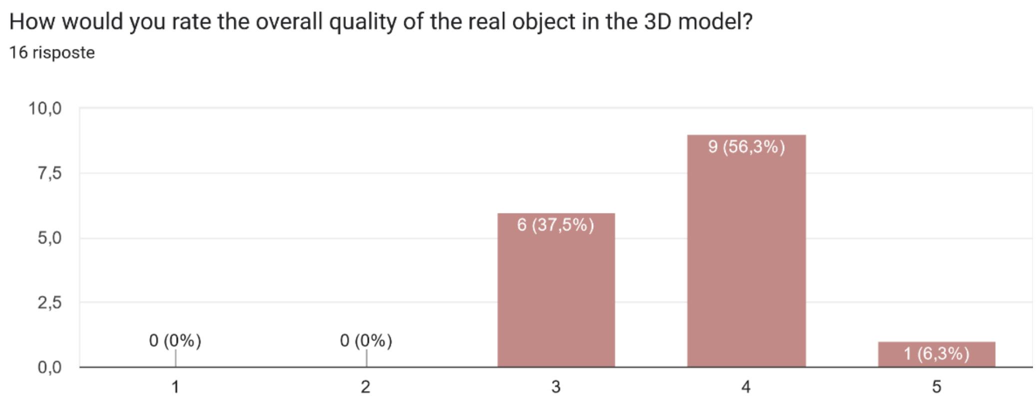

Figure 4.20: Answers to Question 5 (APPENDIX B)

- The majority of the students believe that the environmental lightning conditions have not changed the perception of the AR model: 25% of the participants rated them as perfect, 31.3% gave overall positive answers selecting scores as 3 and 4. Only two people were not satisfied with the way environmental lightning conditions changed the model.

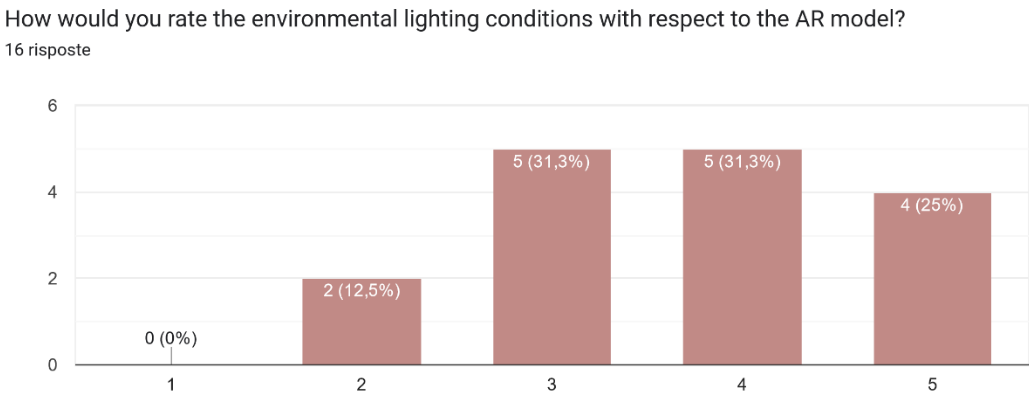

Figure 4.21: Answers to Question 6 (APPENDIX B)

- Similar, if not more positive results have been registered by the question that wanted to understand how much environmental conditions (e.g., background noise, illumination of the room) had influenced the evaluation process. The majority of the participants (31.3%), together with the 18.8%, did not find any limit in the overall environmental conditions when evaluating the 3D models. Only 5 people were extremely influenced by these conditions.
- Lastly, when asked about the possible technical changes that participants would have applied in this regard, seven participants did not make any suggestions, while three participants highlighted particularly the lack of stability of the 3D models. Some also linked this problem with the limited FoV provided by the visor. Further suggestions regarded also the possibility to interact with the objects, namely, to freely move and rotate them, as well as the need to find a more effective selecting method. I have already mentioned this problem at the beginning of some training sessions in section

3.6.2. One last comment regarded the suggestion to use a different kind of device with respect to Microsoft HoloLens 1, as it causes headaches when using it for a prolonged amount of time.

4.4.3 System usability section

This section aims at focusing on the level of usability of the device, as well as on the overall experience. I have asked the participants to answer the questions particularly bearing in mind a possible use in museums or cultural heritage sites of this kind of IT system.

- 43.8% of the participants has found Microsoft HoloLens 1 an adequate device to use in the experience. However, a considerable 25% of the students would have rather chosen another AR device. With regard to its wearability, 37.5% of the participants found the visor quite difficult to wear, while 31.3% did not have any particular problem with it.

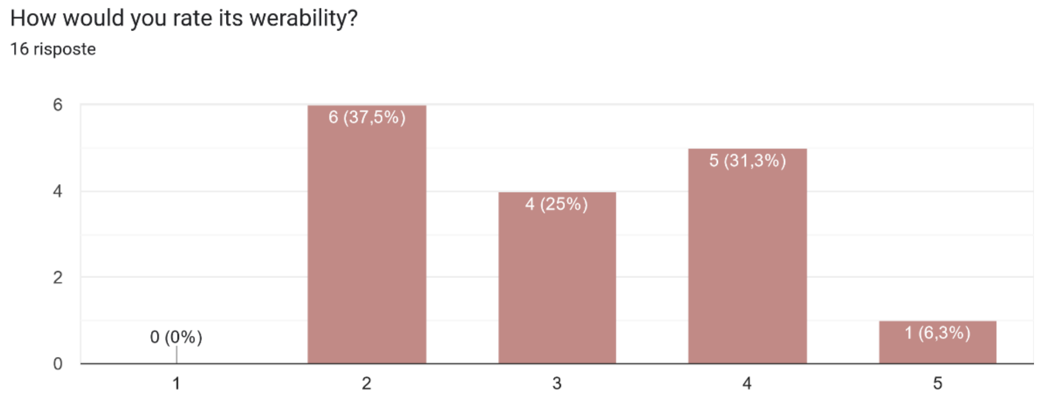

Figure 4.22: Answer to Question 10 (APPENDIX B)

- 11 participants (68.8%) gave the worst scores to the width of the FoV, which confirms some of the comments that have been analysed in the previous section. The remaining 31.3% was not as much influenced by this possible limitation.

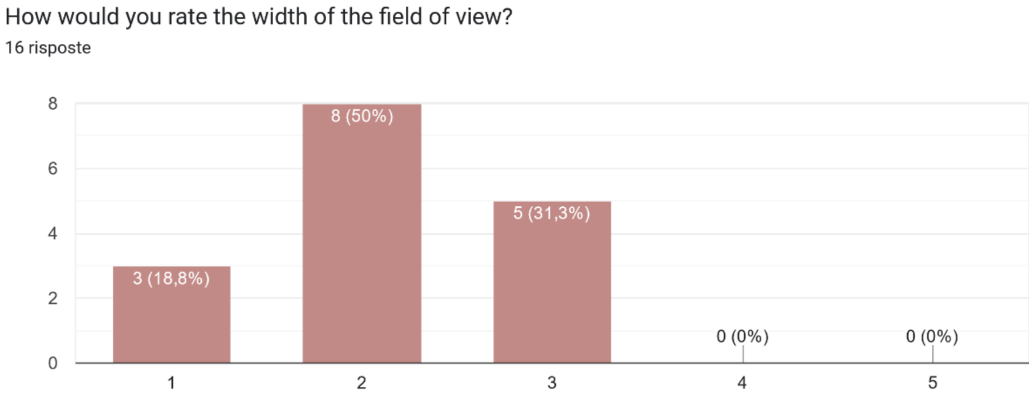

Figure 4.23: Answer to Question 11 (APPENDIX B)

- When asked whether they used voice commands, hand gestures, or both, 62.5% of the participants asserted they used prevalently gestures, while 37.5% tried both types of commands. No one was comfortable in using only voice commands.
- Gestures have been overall rated positively as shown in *Figure 4.23*. However, 3 participants had struggles in using gestures to interact with the interface.

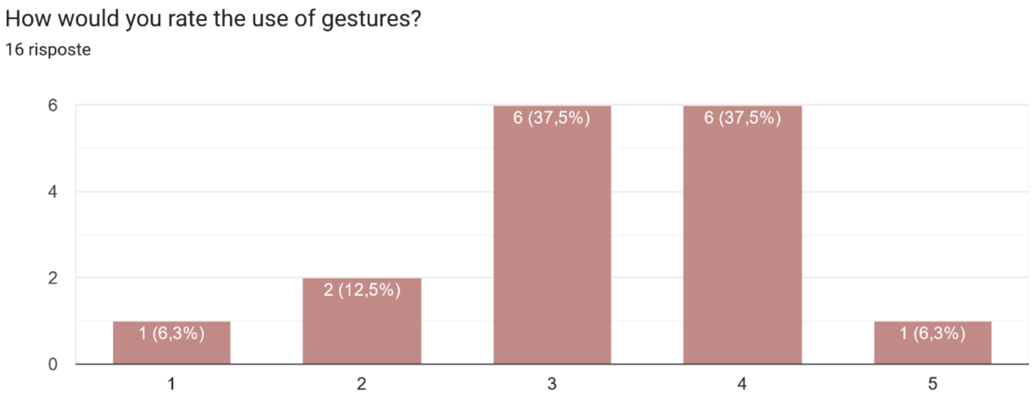

Figure 4.24: Answer to Question 13 (APPENDIX B)

- With regard to the system usability, half of the participants believes it would be quite difficult for people with no practical background to use this kind of headset autonomously. On the contrary, 31.3% thinks there would not be relevant problems in this respect.

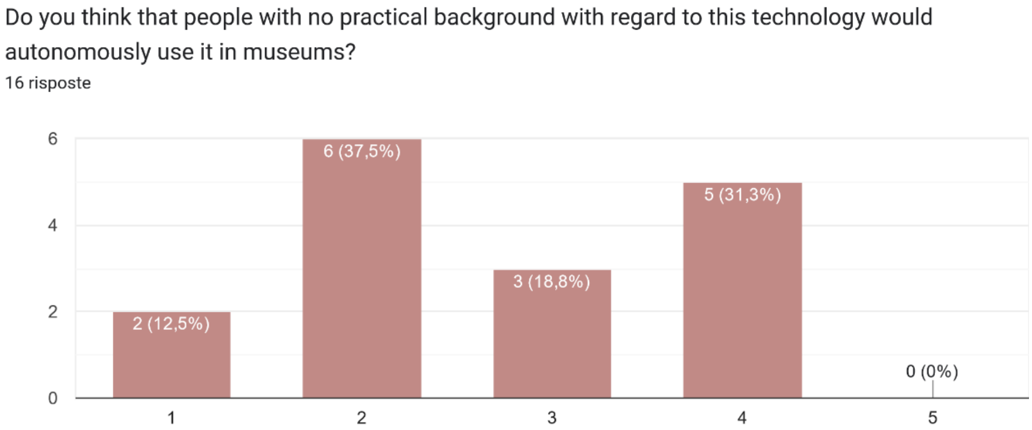

Figure 4.25: Answer to Question 14 (APPENDIX B)

- As a consequence, 37.5% agrees in saying that the level of difficulty would be quite high, with 25% of the participants stating the opposite. Still, *Figure 4.25* demonstrates that 43.8% believes a preliminary training would be essential before potential visitors could be autonomous in using an AR application alone.

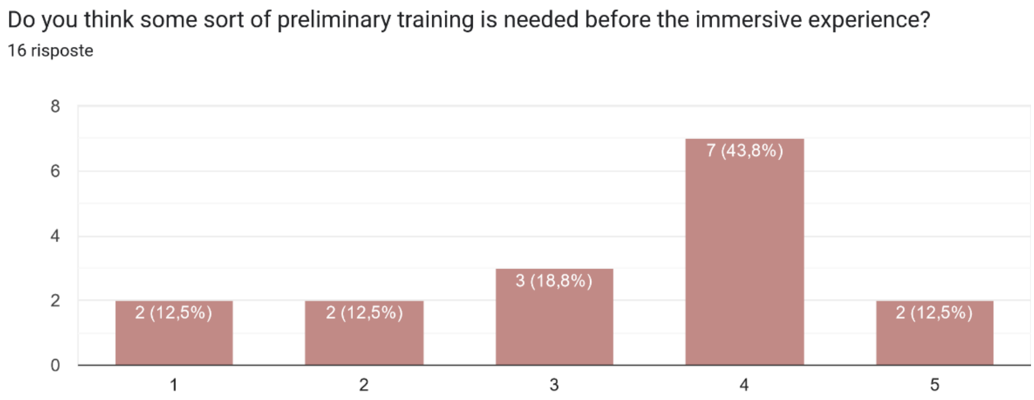

Figure 4.26: Answer to Question 16 (APPENDIX B)

- In conclusion, I asked to suggest further implementations in the system. Here again, some referred to the limited FoV and to the need to make gesture recognition more efficient. Stabilisation has been mentioned again, as some participants found it hard to comfortably wear the device, which forced them to reduce their movements in general. Furthermore, one student in particular suggested the need to add a short tutorial in addition to the preliminary explanation part at the beginning of the experience. Lastly, two comments in particular were referred to the comparison between the VR and AR experience. The students stated that they believe the former would rather take part in a VR experience, rather than in an AR one, as the level of immersiveness is higher and the visor is way more comfortable. I reckon such a statement is definitely driven by the use of Microsoft HoloLens 1, i.e., a visor that was released in 2017. It would be interesting to see if things would change when employing a more recent visor, whose wearability would help users in enjoying more their immersive experience.

CONCLUSION

The general purpose of this thesis is to provide the readers with a complete overview on the immersive technologies spectrum to enhance their knowledge in this regard. In this way, they are more prone to be curious about Mixed reality in all its forms, and to experiment all the possible uses and applications also on a daily basis.

In particular, I focused on the application of MR technologies in a cultural heritage framework, such as museums, galleries and exhibits. This use can potentially involve a large number of people with different education backgrounds and ages. Thus, the primary aim of this study is to prove that immersive technologies experiences in a specific field (in this case in museums and cultural heritage sites) are accessible to all kinds of people, regardless of age, study, or preliminary knowledge.

First, the thesis analyses some of the most important examples of MR applications in the CH field with the intent of triggering readers' curiosity and presenting just a glimpse of the infinite number of potentialities. Consequently, there was the need to try first-hand the impact of a cultural heritage immersive application on a group of participants, who would resemble in some way the possible visitors of a museum or a site. For this reason, it was essential that the participants to the immersive experiences had little or no knowledge of the technology employed. The project participants had to take part in had the two main purposes. The former was to subjectively evaluate a set of 3D models in VR and AR environments. This aimed at better understanding what kinds of characteristics real objects have to maintain in the virtual environment and how these are compatible with the kind of device used. The latter is more strictly related to the way possible visitors deal with the adopted devices and how difficult they find the overall management of the stimuli they receive from the experience itself.

In this regard, the data collected after the subjective evaluation tests conducted both in Virtual and Augmented reality, showed how the models included in the VR experience gave all predictable results. This means that, in most of the cases, models with an objectively-lower quality (measured in numbers of triangles approximating the surface) have received low scores, while higher grades were scored by models with a high representation quality (surfaces were approximated with a huge number of triangles). What must be noted here, is that participants overall felt quite at ease when wearing the VR device (i.e., Oculus Quest 2) as it could easily adhere on their faces, and they felt it stable while moving around the room to look closer at the objects. On the contrary, models superimposed in the AR environment in the second phase of the experiment have received opposite results. Indeed, the mean opinion scores of the lower-quality models were always higher than those of the higher-quality ones. During this experience, contrary to what had happened in the VR context, participants had several problems in regulating the visor (i.e., Microsoft HoloLens 1) comfortably on their faces. At the end of the experience, they also talked about some stability problems in the 3D models that are strictly connected to the quality of each object and how powerful the device used really is in terms of hardware and software. Ultimately, the higher the quality of the model, the more it is prone to lack in stability if the device finds it hard to support all that complexity of the object. The trend that is possible to notice when considering the results from the VR and the AR evaluation tests are that lower-quality models (from 1% to 10% quality) have registered higher MOS in AR with respect to VR. On the contrary, higher-quality levels (from 20% to HQ) all have higher rates in VR with respect to AR.

A further consideration when talking about the subjective evaluation tests is that within the same kind of reality, models' rates vary according to what they represent. For this reason, landscapes are more difficult to evaluate as they are rich in particulars in real life. These are difficult to reproduce faithfully in 3D models, hence the lower scores given to Abbey and Valley models in VR with respect to Lidded Ewer and Mercedes.

Moving on with the second phase of the experiment, when considering the answers to the questionnaires, in both the VR and AR situations models and their relationship with the virtual environment on one hand and the real environment on the other are positively rated, with no particular problems worth mentioning. More relevant results appeared in the second section of each questionnaire (i.e., "System usability"), as firstly some remarks have been made with respect to the visors. In this regard, problems with Oculus Quest 2 were linked primarily to the fact that it has to be worn without glasses, which resulted in some visualisation problems for participants with specific eye diseases. With respect to the Microsoft HoloLens 1, as already mentioned before, the device was not perceived as comfortable to wear due to its weight. In addition, in this case it could be worn over glasses, yet this in some way made it more difficult to find its correct position on the nose and therefore on the rest of the face.

Nonetheless, with respect to the questions regarding the use of these kinds of applications by people with little or no preliminary knowledge in this field, participants are positive in stating that people should not encounter any difficulty in using the devices autonomously. This applies particularly to the Oculus Quest 2, as its use is more intuitive, and controllers certainly aid users in interacting with the buttons in the virtual interface. On the contrary, Microsoft HoloLens 1 may require some sort of preliminary training before being used, as it supports both hand gestures and voice commands that have to be performed precisely. The selecting procedure is also quite far from immediate, which makes this visor definitely less user-friendly than its VR counterpart in this project. However, what has to be remembered here is that Microsoft HoloLens 1 was released in 2017, which makes it slightly obsolete when comparing it with its latest versions.

All this considered, I believe that further studies can be conducted in the future in order to investigate deeper on the connection between possible visualisation problems when using the Oculus Quest 2 and specific eye diseases in particular. It would be useful also to understand if these sorts of devices could be able to correct specific diseases according to each necessity once users wear them. I would also suggest future studies similar to this in the AR environment but with a more recent device, to understand whether some general problems that have arose during the tests are linked to Microsoft HoloLens 1 in particular or have to be applied to the widest spectrum of AR.

To conclude, I am positive in saying that both VR and AR applications can equally bring essential implementations when employed in museums and cultural heritage sites. Each kind of reality is able to provide alternative and more engaging ways in telling the past and connecting it to both present and future times in many different ways. I know for sure that this innovative kind of frontier will continue to develop in the next years and increasingly more people will fully get its immense potentialities.

APPENDIX A
MR in the Cultural heritage framework - evaluation test: translating real objects into 3D models (VR version)

1. Do you already have some kind of knowledge with respect to this technology? (from “beginner” to “expert”)

Section 1: Technical Evaluation

2. How well is the 3D model registered in the environment? (from “very bad” to “very good”)
3. How would you rate the deepness representation achieved through stereoscopic vision? (from “very bad” to “very good”)
4. How would you rate the Level of Detail (LoD)l of the 3D model? (from “very bad” to “very good”)
5. How would you rate the overall quality of the artefact in the 3D model? (from “very low” to “very high”)
6. How immersive do you think your experience was? (from “not immersive at all” to “fully immersive”)
7. Would you improve the model in some way? If so, what changes would you apply? (short answer)

Section 2: System Usability

8. Do you believe the device used (i.e., Oculus Quest 2) was appropriate for this kind of purpose? (form “not appropriate at all” to “very appropriate”)
9. Do you think that people with no practical background with regard to this technology would autonomously use it in museums? (from “not at all” to “absolutely so”)
10. How difficult do you think they would find it? (from “impossible” to “very easy”)
11. Do you think some sort of preliminary training is needed before the immersive experience? (from “necessary” to “not needed at all”)
12. Which implementations of the system would you suggest? (short answer)
13. Do you wear glasses? (y/n answer)
14. If so, comment whether you found any difficulties. (short answer)

APPENDIX B

MR in the Cultural heritage framework - evaluation test: translating real objects into 3D models (AR version)

1. Do you already have some kind of knowledge with respect to this technology? (from “beginner” to “expert”)

Section 1: Technical Evaluation

2. How well is the 3D model registered in the environment? (from “very bad” to “very good”)
3. How would you rate the deepness representation achieved through stereoscopic vision? (from “very bad” to “very good”)
4. How would you rate the detailed level of the 3D model? (from “very bad” to “very good”)
5. How would you rate the overall quality of the real object in the 3D model? (from “very low” to “very high”)
6. How would you rate the environmental lightning conditions with respect to the AR model? (from “very bad” to “very good”)
7. How much do you believe the environmental conditions (e.g., background noise, illumination of the room) have affected your general experience? (from “not at all” to “a lot”)

8. Would you improve the model in some way? If so, what changes would you apply? (short answer)

Section 2: System Usability

9. Do you believe the device used (i.e., Microsoft HoloLens 1) was appropriate for this kind of purpose? (form "not appropriate at all" to "very appropriate")
10. How would you rate its wearability? (from "not comfortable at all" to "very comfortable")
11. How would you rate the width of the field of view? (from "not adequate at all" to "very adequate")
12. Have you used voice commands or gestures? ("voice commands", "gestures", "both")
13. How would you rate the use of gestures? (from "impossible" to "very easy")
14. Do you think that people with no practical background with regard to this technology would autonomously use it in museums? (from "not at all" to "absolutely so")
15. How difficult do you think they would find it? (from "impossible" to "very easy")
16. Do you think some sort of preliminary training is needed before the immersive experience? (from "necessary" to "not needed at all")
17. Which implementations of the system would you suggest? (short answer)

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RIASSUNTO

Il presente elaborato nasce dalla congiunzione di due delle esperienze formative a cui ho avuto modo di prendere parte durante il mio percorso magistrale. La prima è stata la partecipazione al corso di Immersive Technologies tenuto dai Professori Milani e Zanuttigh, durante il quale ho avuto la possibilità di apprendere nozioni teoriche e pratiche riguardo le tecnologie immersive nel loro spettro più ampio. La seconda è l'esperienza di stage intercurriculare svolto presso Palazzo Bo, dove ho potuto immergermi in una realtà museale di spicco per la nostra Università. In questa sede ho avuto modo di svolgere visite guidate sia in italiano che in inglese, di occuparmi dell'organizzazione di eventi inerenti al progetto VisitUnipd e di gestire le principali piattaforme social dello stesso. Da queste esperienze è nato quindi lo spunto che è stato poi sviluppato nel corso della presente tesi, la quale si prefigge l'obiettivo di esplorare il mondo delle tecnologie immersive associato all'ambito museale. Sono state quindi indagate le possibili applicazioni in merito, per poi fornire un apporto originale all'argomento attraverso le fasi del progetto esposto negli ultimi due capitoli dell'elaborato. Sono stati pertanto effettuati dei test soggettivi sulla visualizzazione di oggetti tridimensionali sia in realtà virtuale (RV) che in realtà aumentata (RA); i partecipanti al progetto sono stati un cospicuo numero di studenti dell'insegnamento di 3D Augmented Reality tenuto dallo stesso Professor Milani ed erogato dal corso di laurea magistrale di ICT for Internet and Multimedia dell'Università di Padova.

L'elaborato è stato quindi così strutturato:

- Il primo capitolo, dal titolo "General Overview on Mixed reality and its applications" si sviluppa approfondendo la storia e l'evoluzione delle tecnologie immersive. Si è poi passati ad una sezione interamente dedicata alle definizioni di realtà aumentata, realtà virtuale e realtà estesa al fine di porre solide basi teoriche e fornire al lettore meno avvezzo una generale visione d'insieme sulle diverse sfaccettature legate alle tecnologie immersive. Una successiva sezione si occupa quindi di approfondire quelli che sono i principali dispositivi attraverso cui immergersi in tali realtà alternative, esponendo dettagli più specifici riguardo ai metodi di acquisizione del mondo reale e della sua relativa trasposizione in quello virtuale. Il primo capitolo si chiude infine con una panoramica sui principali campi di applicazione delle tecnologie immersive al giorno d'oggi, tra i quali compaiono l'architettura e l'industria edile, il mondo del commercio al dettaglio, la prevenzione in ambito lavorativo, l'ambito sociosanitario e quello educativo.
- Il secondo capitolo, dal titolo "AR and VR applications in the cultural heritage framework", è interamente dedicato allo studio dell'utilizzo di tecnologie immersive in ambito museale e in altri siti appartenenti al patrimonio culturale. Con la sicura certezza dell'inestimabile importanza di una tale collaborazione tra l'ambito tecnologico e il mondo della cultura, si è investigato sul modo in cui questa cooperazione possa innegabilmente portare benefici a turisti e visitatori. Ad essi è garantita la possibilità di vivere esperienze altamente immersive che possono ottimizzare la visita e

rendere più vivido nella memoria il ricordo della stessa. È quindi introdotto il concetto di “smart tourism” in tutte le sue declinazioni, per poi concentrarsi sul modo in cui tali esperienze possano essere percepite e assimilate dai fruitori del servizio. Questo aspetto in particolare è stato tenuto fortemente in considerazione durante la stesura del questionario di valutazione soggettiva sottoposto ai partecipanti al progetto una volta terminata la loro esperienza in realtà virtuale o aumentata. Dopo un breve excursus su reperti e oggetti museali, sulla loro conservazione e la relativa trasposizione in modelli tridimensionali, si è proseguito con una sezione dedicata all’analisi dei possibili aspetti etici che portano tuttora a ragionamenti scettici in merito alla collaborazione tra tecnologia e ambiente culturale. Vengono poi presentati alcuni esempi pratici di tecnologie immersive applicate all’ambito museale: sono elencate e descritte nel dettaglio alcune pionieristiche applicazioni che hanno portato un contributo essenziale alla valorizzazione del patrimonio culturale italiano ed europeo.

- Il terzo capitolo, come suggerito dal titolo “Project: A subjective evaluation of cultural heritage 3D models in VR and AR environments”, descrive il progetto già menzionato precedentemente introducendone i partecipanti, i modelli tridimensionali utilizzati e i loro diversi metodi di acquisizione, per poi concentrarsi sulla descrizione dei due visori che hanno reso possibili le esperienze immersive in realtà virtuale e aumentata, rispettivamente l’Oculus Quest 2 e il Microsoft HoloLens 1. Sono infine riportate le diverse fasi dei due test condotti (il primo in RV e il secondo in RA), che riguardano la preparazione dell’ambiente in cui si sono svolte le sperimentazioni, la loro esecuzione e l'elaborazione del questionario valutativo dell'intera esperienza.

- Il quarto e ultimo capitolo, "Data Analysis", espone infine i dati provenienti dai test analizzati nel capitolo precedente. Sono stati riportati, sia per le rilevazioni in RV che per quelle in RA, i valori medi delle valutazioni soggettive per i singoli modelli 3D usati. Una seconda sezione, invece, riporta e analizza le risposte ai due diversi questionari valutativi.

Verranno qui di seguito approfonditi con maggior dettaglio i contenuti di ciascun capitolo.

Con il supporto di precedenti studi nel settore, il primo capitolo cerca di delineare la definizione di tecnologie immersive come un sistema che combina l'ambiente reale con quello virtuale che è di fatto interattivo e tridimensionale (Azuma, 1997). Essenziali in questo contesto sono anche le informazioni sensoriali percepite dagli utilizzatori del sistema, alle quali si aggiunge anche una capacità computazionale e digitale rilevante per permettere un'esperienza il più realistica possibile. Si prosegue dunque con una panoramica sull'evoluzione storica di questo tipo di tecnologie, i cui primi tentativi risalgono agli anni Trenta del XIX secolo, con la creazione del primo stereoscopio della storia da parte di Charles Wheatstone. Lo strumento permetteva infatti di percepire immagini bidimensionali come oggetti tridimensionali sfruttando i fondamenti della visione stereoscopica. Il momento di maggiore fervore e interesse per questo tipo di tecnologie si deve però far risalire alla seconda metà del XX secolo, il tutto dovuto alla sempre maggiore diffusione di dispositivi elettronici e sistemi operativi sempre più performanti e all’avanguardia. Vengono quindi citate alcune delle invenzioni pioneristiche di questa fase storica, tra cui compaiono il “Sensorama” di Morton Heilig del 1957 che rivoluzionò il mondo del cinema con un primo tentativo di pellicola multisensoriale, o la celebre “Spada di Damocle” di Ivan Sutherland che nel 1968 creò così il primo “Head Mounted Display” (HMD), nonché il primo avveniristico prototipo di visore di realtà virtuale. Nuove tecnologie e dispositivi hanno poi continuato a svilupparsi nei decenni successivi soprattutto negli Stati Uniti, dove questo tipo di evoluzione correva parallela a quella legata alle tecnologie militari e spaziali. Contemporaneamente, colossi nipponici dell’industria videoludica del calibro di Nintendo e Sega stavano sperimentando e lanciando sul mercato console di gioco in RV che si rivelarono tuttavia fallimentari. Tuttavia, solo con l’esponenziale e rapidissimo progresso tecnologico arrivato all’inizio del Ventunesimo secolo, l’utilizzo delle tecnologie immersive ha visto un’espansione anche verso ambiti di applicazione più vari. Dopo questa prima analisi storica dell’argomento di interesse, si è andati a definire il concetto di “Reality-Virtuality Continuum” introdotto per la prima volta nel 1994 da Milgram e Kishino; il Continuum visualizza, agli estremi di una linea continua, l’ambiente reale e quello virtuale che limitano quindi quella che viene definita realtà mista (RM), che comprende sia la realtà aumentata che quella virtuale. Da questa definizione è stato poi possibile delineare il significato della prima, intesa come sovrapposizione di elementi virtuali in un ambiente reale che quindi coesistono simultaneamente. A sua volta, la realtà virtuale non ammette nessuna contaminazione da parte dell’ambiente reale, venendo definita dagli esperti come un ambiente sintetico e realizzato completamente attraverso dispositivi dalle elevate capacità computazionali. Un'ultima definizione che viene fornita è quella di realtà estesa (XR), alla quale vengono attribuiti significati differenti: alcuni ricercatori affermano che si tratti di un termine generico per indicare tutti i tipi di realtà precedentemente menzionati (realtà mista, aumentata e virtuale), altri che escluda nella sua definizione la realtà virtuale. Sono poi state analizzate le caratteristiche principali dei dispositivi di realtà mista prendendo come riferimento la tassonomia dei ricercatori Milgram e Kishino (1994) che differenzia dispositivi "wearable" (indossabili) da quelli "non-wearable" (non indossabili); a loro volta i primi possono essere "helmets" (caschi) o "headsets" (meno invasivi degli "helmets", sono più simili a occhiali). In questo modo si sono poste le basi necessarie per la comprensione del funzionamento degli HMD (l'Oculus Quest 2 e il Microsft HoloLens 1) che sono poi stati utilizzati nel corso dei test soggettivi descritti nei capitoli 3 e 4.

Seguendo gli studi di Bekele *et al.* (2017), si sono poi delineate alcune caratteristiche comuni alla maggior parte dei dispositivi, quali il tracciamento che determina la posizione dello user ed è usato prevalentemente in contesti di RA; la creazione dell'ambiente virtuale simulando l'ambiente reale con i relativi oggetti che lo compongono che devono essere il più vicini possibile alla realtà; i dispositivi utilizzati, e le interfacce di interazione che mirano ad essere il più intuitive e naturali possibile per garantire un'esperienza piacevole agli user. Il capitolo si conclude con una panoramica generale sugli ambiti principali in cui le tecnologie immersive vengono oggi comunemente utilizzate. Il primo campo preso in considerazione è quello dell'architettura e dell'industria edile, dove ambienti di RM vengono creati per limitare i ritardi di progettazione e i costi di produzione in quanto l'utilizzo incontrollato di materiali viene contenuto. Nella vendita a dettaglio la realtà mista viene introdotta assieme al concetto di "smart retail", con la conseguenza di uno shopping più oculato da parte dei clienti che possono godere anche di un'esperienza di acquisto più immersiva e personalizzata. La prevenzione di incidenti sul lavoro e il sistema sanitario sono sicuramente tra gli ambiti di applicazione in cui la RM ha visto il suo maggiore impiego, portando di fatto risultati che possono permettere concretamente di salvare vite umane. Infine, un'ultima sezione è dedicata all'analisi del ruolo di questo tipo di tecnologie nell'educazione: di particolare rilievo sono i benefici riscontrati negli studenti che appaiono più motivati e invogliati nell'apprendimento. Alcuni studi hanno anche rilevato una maggiore abilità nella risoluzione dei problemi. Inoltre, le tecnologie immersive permettono di abbattere alcune barriere prima invalicabili nell'ambito dell'educazione di persone con differenti gradi di disabilità. Sono state infatti menzionate, tra le altre, alcune applicazioni rivolte a persone ipovedenti che riescono a percepire famose opere d'arte con l'impiego di tecnologia tattile, ma anche metodi alternativi per aiutare persone con disturbi autistici a migliorare e gestire le proprie abilità sociali. Ulteriori studi sono poi stati condotti su persone sorde e pazienti affetti da demenza.

Collegandosi al primo capitolo, il secondo approfondisce in maniera dettagliata l'ambito di applicazione su cui si concentra l'elaborato, quello museale e del patrimonio culturale. Questa nascente frontiera del turismo "smart" vede come punto cardine quello di garantire ai visitatori un'esperienza immersiva e in grado di rimanere impressa nel proprio bagaglio personale. Ogni turista, senza discrezione di età o conoscenze pregresse in merito al sito interessato, è quindi in grado di apprendere i contenuti della visita giocando e divertendosi. A tal proposito viene quindi definito il concetto di *smart tourism*, che si contrappone a quello di turismo di massa che ha visto il suo apice negli anni '90. Lo scopo del turismo *smart* è quindi quello di contrapporsi ad esso presentando un'idea di turismo efficace, capace di arricchire i visitatori e di essere sostenibile per l'ambiente attraverso l'utilizzo della tecnologia. Recenti applicazioni in merito hanno dato la dimostrazione di essersi rivelate molto efficaci durante la pandemia di COVID-19: tour immersivi da remoto di famosi musei e gallerie d'arte di tutto il mondo hanno permesso a chiunque, dalla propria casa, di godere ugualmente dei tesori che custodivano. Strettamente collegato al concetto di *smart tourism* è quello della *gamification*, un termine coniato nei primi anni 2000 per esprimere l'applicazione di dinamiche solitamente legate al mondo dei videogiochi a diversi ambiti di vita sociale. In ambito museale e del patrimonio artistico, Xu *et al.* (2016) sono stati tra i primi ad occuparsi di come tali applicazioni potessero giovare in questo campo. Sono arrivati alla conclusione che, ad esempio, la visita di nuove città o siti con l'integrazione di dinamiche di gioco permette allo user di ottenere maggiori informazioni sul luogo visitato in un ambiente stimolante e dinamico. Importante da tenere in considerazione, tuttavia, è quanto positivamente venga percepita questa nuova frontiera del turismo da un pubblico ampio e molto spesso poco abituato all'utilizzo della tecnologia in generale. Per questo motivo è essenziale prendere in considerazione alcuni parametri di accettazione tecnologica (TAM, Technology Acceptance Model) e di propensione alla tecnologia (TR, Technology Readiness). A tal proposito recenti studi (Chen and Chan, 2014) hanno dimostrato quanto sia importante la percezione che i visitatori hanno dell'ambiente circostante per accettare poi il possibile utilizzo della tecnologia. Deve essere infatti l'ambiente stesso a invogliare il visitatore ad un'implementazione tecnologica, senza la quale sarebbe consapevole di non godersi l'esperienza completa. Considerando inoltre il tipo di test che sarebbero stati condotti come progetto di tesi, con l'aiuto degli studi di Saggio *et al.* (2011) è stato possibile inserire in questo capitolo anche un interessante riferimento al ciclo di restauro di reperti e manufatti in correlazione con il "Reality-Virtuality Continuum" di cui si era discusso nel capitolo precedente. Gli studiosi affermano infatti come sia possibile provvedere al restauro virtuale di manufatti pesantemente compromessi, proponendo così una soluzione efficace, all'avanguardia e più economica per i siti culturali rispetto alla realizzazione di una copia fisica che non garantirebbe lo stesso tipo di esperienza immersiva e interattiva al visitatore. Il capitolo si conclude dunque con l'esposizione di alcuni esempi di progetti nei quali sono state utilizzate le tecnologie immersive in contesti culturali in diverse zone dell'Italia e d'Europa. Si rimanda dunque il lettore alla sezione 2.5 dell'elaborato per poter leggere nel dettaglio le esperienze selezionate in quanto più affini all'argomento trattato in questa tesi.

Dal terzo capitolo, si cominciano a prendere in esame i primi dettagli riguardanti il progetto di valutazione soggettiva di modelli tridimensionali del patrimonio culturale in ambienti di realtà virtuale e aumentata. La prima fase del progetto, quella in realtà virtuale, si è svolta con la partecipazione di 35 studenti del corso magistrale di 3D Augmented Reality tenuto dal Professor Milani. Gli studenti hanno da subito dimostrato grande interesse e curiosità in merito al progetto, cosa che ha contribuito certamente alla sua efficacia. Ai partecipanti è stato chiesto di indossare il visore e valutare, secondo una scala da 1 (pessima) a 5 (ottima), la qualità di 22 oggetti: gli studenti potevano osservarli nell'ambiente virtuale senza limitazione alcuna, in quanto il movimento nella stanza era concesso e fortemente consigliato per poterne valutare con attenzione ogni dettaglio e decretarne la corrispondenza o meno con l'oggetto originale. Anche questo tipo di valutazione è avvenuta all'interno dell'ambiente virtuale. I modelli utilizzati sono rappresentazioni mesh di oggetti in parte direttamente scansionati dai corrispettivi reali, in parte creati con software di design 3D avendo come modelli oggetti comunque realmente esistenti. Per una visione più completa della renderizzazione dei modelli in questione, si rimanda al paragrafo 3.3 dell'elaborato. Una volta terminata l'esperienza virtuale, i partecipanti hanno compilato un questionario di valutazione (APPENDICE A) sull'esperienza generale. È stato loro chiesto di fare particolare riferimento sia alla valutazione tecnica di ogni modello, sia al livello di fruibilità del sistema considerandolo inserito in un sito culturale e utilizzato da visitatori di ogni età e diversi livelli di conoscenza pregressa della tecnologia utilizzata. Ogni domanda del questionario è stata ideata tenendo in considerazione l'ambiente virtuale, le tipologie di manufatti presi in esame e i parametri di TAM e TR della sezione 2.2.2 del capitolo precedente.

Dopo aver introdotto la prima serie di test in realtà virtuale, si è proseguito con la presentazione della seconda parte del progetto, nonché la realizzazione di test soggettivi, questa volta in realtà aumentata. Vi hanno partecipato 16 studenti del medesimo corso della precedente esperienza in realtà virtuale, che in questo caso hanno avuto modo di sperimentare l'utilizzo del Microsoft HoloLens 1. Il test soggettivo consisteva nella valutazione soggettiva dei medesimi modelli utilizzati durante l'esperienza in realtà virtuale. In questo caso, tuttavia, i partecipanti hanno dovuto abituarsi all'utilizzo di un nuovo visore che non prevedeva l'uso di controller per spostare il cursore e selezionare gli elementi, ma hanno anche dovuto prestare particolare attenzione alla possibile incidenza di fattori esterni nel condizionare la visualizzazione dell'oggetto tridimensionale. Al termine di ogni test, è stato chiesto ai partecipanti di compilare il questionario (APPENDICE B) relativo alla valutazione tecnica dell'esperienza e del livello di fruibilità del sistema nel suo complesso. Anche in questo caso, si è chiesto di rispondere alle domande considerando l'ipotesi di un possibile utilizzo dell'applicazione in contesto museale con visitatori poco avvezzi al tipo di tecnologia utilizzata.

Dopo aver esposto nel dettaglio i parametri dei due test, infine, il quarto ed ultimo capitolo analizza i dati raccolti sia dalle valutazioni soggettive che dai questionari di valutazione finali. Per entrambe le esperienze, sia quella in RV che quella in RA, i dati della prima fase (valutazione soggettiva) sono stati raccolti e successivamente raggruppati per tipo di modello. In questo modo è stato possibile notare come i diversi livelli di dettaglio di ogni modello siano stati valutati in base alla qualità percepita dagli studenti. In generale, per quanto riguarda l'esperienza in RV, non sono state registrate anomalie di alcun tipo: tutti i modelli hanno avuto una valutazione più o meno alta, ma comunque in linea con il livello di dettaglio corrispondente. L'unico caso in cui questo non è avvenuto, tuttavia, è stato riscontrato nel modello *Valley*, in quanto il modello originale (quindi quello dalla qualità maggiore) è stato valutato con un punteggio decisamente inferiore alla corrispettiva variante degradata del 50%. Sono state infine riportate le risposte alle singole domande presenti nel questionario. Anche in questo caso non sono stati riscontrati dati anomali, in quanto i partecipanti, molti dei quali con scarsa se non addirittura inesistente esperienza pregressa in questo campo, hanno trovato il test immersivo, con i modelli di più elevata qualità inseriti adeguatamente nell'ambiente virtuale. Per quanto concerne invece il livello di fruibilità del sistema, la maggior parte degli studenti ha valutato l'esperienza come adatta anche a persone senza conoscenze preliminari in merito alla tecnologia e al visore utilizzati. Alcuni hanno tuttavia fatto notare come potrebbe essere necessaria, una volta inserita una simile esperienza in un sito di rilevanza culturale, la supervisione di un esperto per far fronte a comprensibili dubbi o problemi tecnici. Particolare attenzione è stata poi quella diretta ai partecipanti che presentavano difetti visivi per i quali devono indossare occhiali da vista, in quanto sono stati costretti a toglierli per utilizzare il visore. Si è voluto pertanto indagare se l'assenza del mezzo di correzione dei disturbi visivi avesse potuto in qualche modo compromettere la visualizzazione dell'oggetto e quindi anche la stessa valutazione soggettiva. Le risposte in merito hanno fornito spunti particolarmente interessanti, in quanto alcuni hanno effettivamente riportato difficoltà nella visualizzazione e nella messa a fuoco, con correlata mancanza di certezza del valutare l'oggetto. Inoltre, l'affaticamento oculare è stato lamentato anche da coloro che normalmente non indossano gli occhiali, nonostante siano state seguite tutte le linee guida relative al corretto utilizzo del visore e sia stato rispettato il limite temporale di utilizzo consecutivo del dispositivo di 20 minuti.

Per quanto concerne invece i risultati dell'esperienza in RA, essi sono strettamente legati alle capacità hardware e software del dispositivo utilizzato per i test, il

Microsoft HoloLens 1. Si è infatti osservato come i modelli a più alta risoluzione (specialmente dal 20% di degradazione della qualità in su) abbiano registrato valori parecchio bassi nella scala di valutazione soggettiva. Inoltre, il valore più alto registrato è stato di 3,54 su una scala di 5, rispetto al corrispettivo di 4,5 in RV. La motivazione che potrebbe spiegare questi risultati può essere trovata nella complessità dei modelli a maggiore risoluzione: in quanto più dettagliati, hanno più superfici definite che possono quindi causare problemi di visualizzazione scattosa nel dispositivo. Questo problema, chiaramente, non si presenta con modelli di qualità più bassa, che hanno infatti ricevuto valutazioni MOS più elevate. Queste considerazioni sono sorte anche dalle risposte del questionario finale. I partecipanti hanno valutato positivamente l'interazione tra ambiente reale e oggetto virtuale, ma hanno lamentato una certa difficoltà nell'indossare e utilizzare il visore stesso. Anche il limitato campo visivo fornito dal visore ha certamente contribuito ad abbassare il livello di piacevolezza nell'immergersi in una tale esperienza di RA. Per quanto riguarda infine la possibile replicabilità di una simile esperienza in ambito museale o del patrimonio culturale, i partecipanti hanno affermato che potrebbe essere efficace, ma servirebbe una fase di training più avanzata rispetto ad un'esperienza in RV con il visore Oculus Quest 2, il cui metodo di utilizzo è certamente più immediato. Anche il livello di immersione è stato definito inferiore rispetto a quello dei test precedenti, ma questo è indubbiamente legato alla natura stessa della tecnologia immersiva impiegata in questo contesto.

Al termine dell'analisi dei dati, sono state poi tratte le dovute conclusioni sulle informazioni raccolte, tenendo anche in considerazione l'apporto di carattere prettamente teorico della ricerca bibliografica sviluppata nei primi due capitoli.

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