
Optimization of Immersive Virtual Reality Experiences for the Dissemination of Cultural Heritage Reconstructions

PhD Thesis



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Virtual reconstruction of Cultural Heritage (CH) is one of most relevant topics in immersive Virtual Reality (iVR) research, due to the technology's capacity to visualize lost CH that would otherwise be impossible. Today, the wide availability of affordable hardware and software for iVR development suggests a promising future. Despite the maturity and accessibility of iVR technology, its use for disseminating CH reconstructions still faces significant challenges. To explore its potential and limitations, this thesis presents four studies addressing the question of how to optimize current iVR technology for the dissemination of CH reconstructions from different perspectives:

- The first study presents a critical literature review of 94 articles on iVR for CH dissemination, offering a broad overview of this research area. It focuses on how CH reconstructions are created, how iVR experiences are designed, and how they are evaluated, proposing best practices and future research directions.
- The second study introduces a tool for the assessment of Level of Detail, validated with both professional and 3D modeling students yielding satisfactory results. This complements the first study by supporting the classification of iVR experiences and facilitating the development of 3D models, particularly for novice users.
- The third study proposes and assesses a procedure for developing and validating 3D models of CH reconstructions, focusing specifically on the use of virtual agents due to their greater complexity in creation and their advantages in iVR environments. This procedure was implemented in an iVR experience validated with 60 participants, yielding positive results and providing insights into how demographic factors influence iVR experience design.
- The fourth study designs and evaluates an iVR CH dissemination experience in a museum setting with progressively increasing interaction levels. Tested with 171 participants of varying ages, it identifies effective design patterns tailored to different user profiles. While an iVR experience can be satisfactory for a broad range of users when certain aspects are carefully addressed, this study shows that user-adapted design leads to better outcomes and highlights the need to leverage presence and interaction in iVR design.

These studies demonstrate that: 1) Development processes can be enhanced with purpose-built tools; 2) visual quality and interaction design are crucial for user experience in iVR; 3) user demographics significantly influence experience design; and 4) the area of research can and should be strengthened through robust evaluation of outcomes.

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AUTHOR'S DECLARATION

La tesis “Optimization of Immersive Virtual Reality Experiences for the Dissemination of Cultural Heritage Reconstructions” que presenta D. Bruno Rodríguez García para optar al título de doctor, ha sido realizada dentro del programa “Doctorado en Ingeniería y Tecnologías Industrial, Informática y Civil” en el Área de Lenguajes y Sistemas Informáticos, perteneciente al Departamento de Ingeniería Informática de la Universidad de Burgos, bajo la dirección del doctor D. Andrés Bustillo Iglesias. El director autoriza la presentación del presente documento como memoria para optar al grado de Doctor por la Universidad de Burgos cumpliendo los requisitos para poder optar a la Mención Internacional.

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El doctorando:

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Part I

PhD Dissertation

PREFACE

This part consists of two chapters. The first addresses the key concepts necessary for understanding this thesis. The second presents the motivations and objectives of the research, which are addressed in *Part II* as journal articles and subsequently discussed in *Part III*.

INTRODUCTION

This chapter presents the key concepts addressed throughout this thesis. The central topic of the research is immersive Virtual Reality (iVR). Although this technology has a wide range of applications, this thesis focuses specifically on its use for the dissemination of Cultural Heritage (CH) reconstructions. *Section 1.1* introduces the fundamental concepts of iVR, including its technology, visualization, and main features. *Section 1.2* examines the characteristics of CH reconstruction, as well as the design of iVR experiences within this domain. Finally, *Section 1.3* and *Section 1.4* outlines the advantages and limitations of this technology respectively.

1.1 Virtual Reality: an evolving concept

Virtual Reality (VR) emerged in the 1950s with the development of the *Sensorama*, a mechanical device invented by Morton Heilig that combined stereoscopic images, surround sound, and smells (Heilig, 1962). However, the first VR headset or Head-Mounted Display (HMD) connected to a computer did not appear until the 1960s, with Ivan Sutherland's *Sword of Damocles* (Sutherland, 1968). This device represented a milestone in the history of VR, as it enabled real-time visualization of simple computer-generated graphics.

The *Sword of Damocles* is situated within the framework of Ivan Sutherland's concept of the *Ultimate Display*, a theoretical device designed to make the experience of virtual environments indistinguishable from reality. In his research, Sutherland (1965) defined VR as “a window through which a user perceives the virtual world as if [it] looked, felt, [and] sounded real and in which the user could act realistically”. This initial, rather utopian definition was later followed by other researchers, such as Steuer's (1992), who described VR “as a real or simulated environment in which a perceiver experiences telepresence”, placing greater emphasis on the sense of being in an environment. One decade later, Burdea and Coiffet (2003) defined VR as “a high-end user-computer interface that involves real-time simulation and interaction through multiple sensorial channels”, highlighting instead the role of user interaction with the environment.

Despite the concept of VR evolved over the years, the term has been consistently used to describe technologies that allow users to immerse and interact with a virtual world by stimulating their senses, thereby highlighting the two key features of VR experiences: presence and interactivity.

1.1.1 VR main concepts

Presence and interactivity are broad features of VR whose definition and optimization will be explored in this thesis. Delving deeper into these key features, two additional complementary characteristics can be observed, being four in total (Mütterlein, 2018):

- *Presence*: refers to the sensation of “*being in an environment*”. A strong sense of presence implies that virtuality imposes itself over physical reality, becoming the dominant reality (Witmer & Singer, 1998), despite the user aware that the environment is computer-generated.
- *Immersion*: refers to the capacity to deliver a convincing simulation and to isolate the user from physical reality (Slater, 2003), for example, through higher realism in visualization. Higher levels of immersion increase the likelihood that virtuality will be experienced as the dominant reality (Cummings & Bailenson, 2016). Thus, immersion relates to the technical capability of a system to elicit presence but does not constitute presence itself.
- *Interactivity*: refers to the user capacity to influence and modify the virtual environment (Steuer, 1992). The degree of interactivity depends on: 1) the speed of interaction, understood as the latency in relation to user input; 2) the number of attributes that can be manipulated and the variety of possible interactions; and 3) the resulting actions produced within the environment.
- *Engagement*: refers to the level of user involvement with the virtual environment (Tcha-Tokey et al., 2016). High engagement reflects strong user motivation to experience the virtual environment. This feature is closely related to the three aforementioned characteristics, as all of them contribute to increasing engagement (Jennett et al., 2008). Engagement may also be enhanced through additional stimuli such as the inclusion of narratives, characters, or game elements within the iVR experience (Schaumburg et al., 2025).

Based on these characteristics, the concept of VR can be segmented according to its technological implementation. On one side, depending on how presence is experienced, it can be divided into low-immersive VR and high-immersive VR also known as iVR. In the former, the user experiences VR through a 2D screen, whereas iVR surrounds the user within large three-dimensional viewing areas (Checa &

Bustillo, 2020a). Although the previously mentioned characteristics are common to both VR and iVR experiences, the latter enables deeper sensory stimulation, which makes these features manifest with greater intensity.

On the other side, depending on how interactivity is implemented, VR and iVR can be classified according to the Degrees of Freedom it provides to the user, distinguishing between three Degrees of Freedom (3DoF) and six Degrees of Freedom (6DoF). *Figure 1* illustrates the difference between a user experiencing iVR with 3DoF and 6DoF in a iVR setting with the axes of movement represented in color. In 3DoF, only rotational movements are allowed, so the virtual environment surrounds the user, and their spatial position remains fixed, preventing interaction. In contrast, 6DoF allows not only rotation the user can move through space and interact with the environment (Rossi et al., 2021).

Since iVR is the modality that allows for the most effective experimentation with its key features, the remainder of this thesis will focus on this technology.

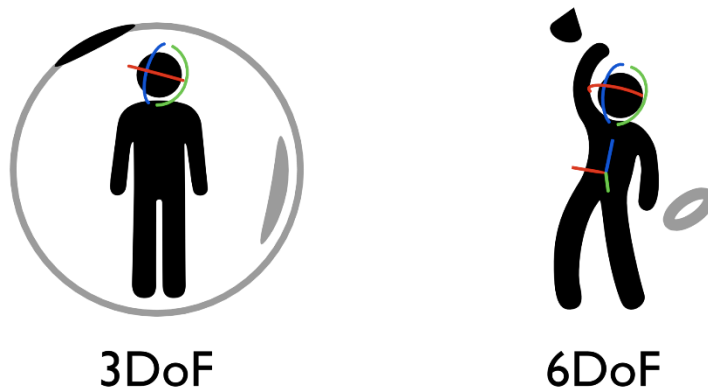


Figure 1. Users experiencing iVR: 3DoF on the left, 6DoF on the right

1.1.2 iVR technology

Although alternative forms of experiencing iVR exist, nowadays the most common way is through an HMD. These devices integrate technological solutions to foster the sense of presence and interactivity.

In order to generate an effective immersion, the HMD presents the virtual environment through two screens positioned very close to the user's eyes, viewed through lenses that adjust the field of view. Images are generated with virtual cameras for each screen of the HMD, produced with a stereoscopic shift of approximately 6 to 7 cm, corresponding to the average interpupillary distance (Woldegiorgis et al., 2019). The images displayed in the HMD adapt to the user's

movements through gyroscopes and tracking sensors, which may be either external or integrated into the HMD (Mehrfard et al., 2019). Considering the implementation of these technological features, modern HMDs can be classified into two main categories (Sukaridhoto et al., 2023):

- *Desktop HMDs* operate connected to a computer. They enable higher simulation quality, with larger and more realistic environments. However, the requirement of a constant connection to a computer reduces portability, and the presence of cables makes them less comfortable to use. These HMDs may rely on external tracking systems or integrate them directly into the device.
- *Standalone HMDs* function independently from a computer. They have lower computational power, which limits the quality of iVR experience, but they are easier to transport and use. These devices usually incorporate tracking systems internally. This category includes both low-end HMDs that are smartphone-based or have very limited processing power (more suitable for 3DoF experiences) and more powerful HMDs that enable 6DoF experiences with higher realism (Anthes et al., 2016).

Figure 2 shows the operation of the stereoscopic shift (left) and the different components that an HMD may include (right), as well as the resulting image projection on each screen. Depending on whether it is a desktop or a standalone device, it may require a wire connection to the computer, while the use of internal or external trackers will vary depending on the device.

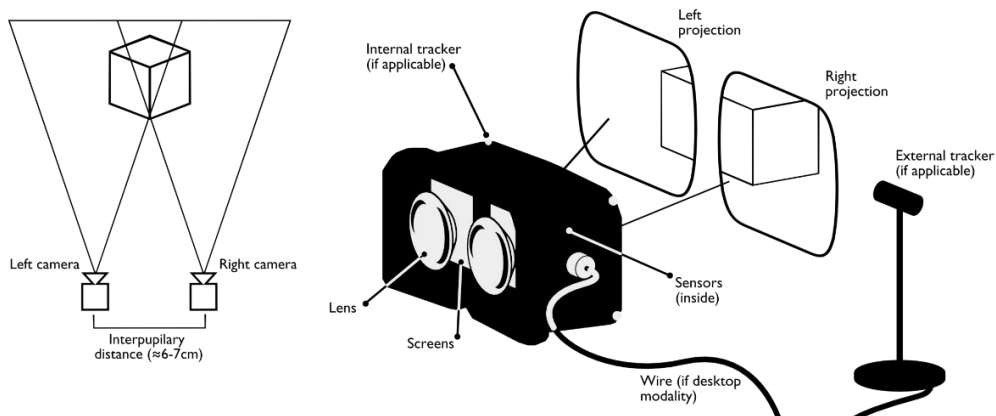


Figure 2. On the left, the capture of images with virtual cameras to produce the stereoscopic shift is shown. On the right, the different parts of an HMD are displayed along with the resulting projection on each screen

Interactivity usually requires 6DoF spatial displacement. It can be achieved through different methods, the most common being active movement or motion-based locomotion, where the user's real physical movement is used as input (Boletsis & Chasanidou, 2022). Although this system is straightforward for users, some implementations present significant limitations, such as being restricted to the physical play area where the iVR is installed. For this reason, secondary locomotion systems are often introduced, among which teleportation is one of the most widely used (Prithul et al., 2021). In addition, HMDs usually incorporate a control system based either on handheld controllers (designed specifically for iVR or more general-purpose) or on hand recognition, known as hand tracking. This latter system is considered more immersive due to the absence of external devices, but it still presents challenges for implementation because of its limited accuracy (Reimer et al., 2023). Ineffective implementation of locomotion or interaction may lead to usability issues and reduced user satisfaction (Avilés-Castillo et al., 2025).

1.1.3 iVR visualization

To generate the sense of presence, an iVR experience should stimulate as many senses as possible. While taste, smell, and touch have been explored in research, their practical application is limited due to cost and technical challenges (Cheng et al., 2025). Thus, vision and hearing are the most stimulated senses, with vision being the most critical, while hearing is often considered secondary due to its lower dominance in capturing user attention (Malpica et al., 2020).

To effectively stimulate vision, the images displayed in the HMD must be updated with high speed and stability to ensure a smooth and continuous visual experience (Sukaridhoto et al., 2023). Images may either be pre-captured or generated in real time. Real-time image generation is computationally demanding, making pre-captured images a valuable strategy particularly when using limited devices such as a smartphone-based standalone HMD. These images can be obtained either through 360° camera capture or by rendering a 3D environment (Ritter & Chambers, 2022). However, pre-captured images restrict iVR experiences to 3DoF, as users can only access viewpoints that were previously recorded, thereby limiting freedom of movement and allowing only head rotation (Attal et al., 2020). Moreover, depending on the capture method, these viewpoints may lose stereoscopic depth, making them less immersive.

The real-time image generation necessarily relies on the creation of an environment composed of 3D models. A wide range of 3D model types exists, but polygonal 3D models remain the most common in the context of iVR and interactive applications due to their flexibility and straightforward integration with development engines (Luebke, 2001). A polygonal 3D model is a vector-based figure

composed of a set of vertices within a three-dimensional Euclidean space. These vertices can be connected to form edges and polygons, thereby enabling the representation of a wide range of object geometries (Chopine, 2011). Materials can be applied to 3D models, working as systems that project images or patterns onto the geometry to provide radiometric properties such as different types of reflections or colors (Deng et al., 2024). *Figure 3* presents, in a horizontal sequence, the process of forming a 3D dice model: beginning with its vertices, followed by the connection of these elements to generate edges and faces, and concluding with the application of images onto the model's surface to produce its final appearance.

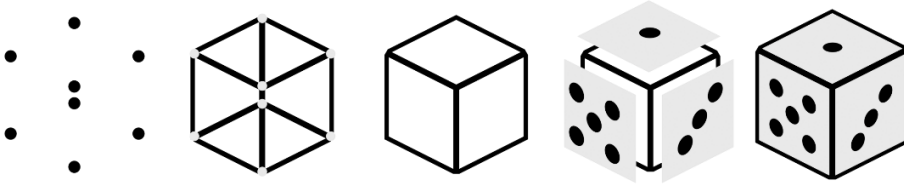


Figure 3. Process of 3D model formation displayed in a horizontal sequence

Furthermore, 3D models can be classified according to their Level of Detail (LoD), which indicates the degree of similarity between an object and its virtual representation. This characteristic is highly relevant in iVR experiences, as a high LoD contributes to greater realism and an enhanced sense of presence (Newman et al., 2022). However, achieving a high LoD typically increases model complexity and computational costs thereby complicating real-time image generation; although this process can be alleviated through the use of 3D model optimization techniques (C. Zhang et al., 2023). This constraint does not affect pre-captured images used in 3DoF experiences, since such content is not generated in real-time. For this reason, 3DoF experiences face fewer restrictions regarding LoD. *Figure 4* displays the difference of LoD in the geometry of the *Stanford Bunny* 3D model. The version on the left shows its original polygon count, while the one on the right is displayed at a lower LoD.

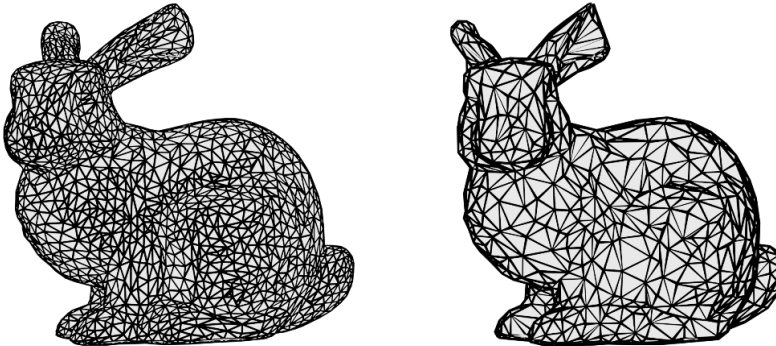


Figure 4. LoD difference in the *Stanford Bunny* model: original LoD (left), reduced LoD (right)

However, iVR experiences can be constrained by visualization-related issues. Poor performance, such as low or unstable frame rates, may result in cybersickness. This condition can cause dizziness or headaches in users, and in more severe cases may lead to stronger symptoms (Chang et al., 2020). The higher the LoD and the greater the number of 3D models displayed on screen, the higher the computational cost, which may cause cybersickness, among other issues.

1.1.4 Design and types of iVR experiences

Presence is the inherent feature of this technology, as its primary purpose is to immerse the user in a virtual environment that may offer varying degrees of interaction. Therefore, depending on the level of interactivity and exploration, iVR experiences can be classified into the following modalities (Checa & Bustillo, 2020a):

- *Passive*: in these experiences, the user cannot interact with the environment, and movement is limited to 3DoF or 6DoF with very restricted mobility.
- *Explorative*: these experiences allow free exploration of the virtual environment, but do not enable direct interaction with it.
- *Explorative Interaction*: these experiences allow both free exploration of the environment and interaction with at least some of its objects.
- *Interactive Experience*: in these experiences, the user can interact with elements of the environment, but movement is restricted to a very limited area.

The choice of each type of experience depends on the intended objectives, with common constraints. On the one hand, greater interaction usually offers more possibilities in the design of iVR experiences. In this sense, more interactive types of iVR experiences can include design elements such as virtual agents or interfaces. Virtual agents are digital characters that interact with or populate a virtual environment. Their use in iVR experiences enhances both engagement and presence (Sylaiou & Fidas, 2022). On the other hand, excessive or poorly implemented interaction may lead to usability issues and reduced user satisfaction (Avilés-Castillo et al., 2025). Moreover, designing interaction is challenging because the thresholds of acceptable vary considerably due to demographic factors such as age or prior experience with technology, a phenomenon known as the novelty effect (Miguel-Alonso et al., 2024). When these constraints are properly managed, greater interaction and exploration enhance user engagement and positive effects, as they enable a more believable simulation. In this regard, the type of iVR experience is related by DoF, the HMD employed, and the interaction system to achieve the best possible sense of presence and interactivity.

Finally, *Figure 5* illustrates the relationship between the most relevant factors in designing an iVR experience. Starting from the center of the figure, it shows the desired visualization conditions (related to the sense of presence) and the intended degree of interaction (related to the interactivity). At the bottom, the issues generated by these two design factors are indicated, along with their impact on the key features of iVR experiences. Upwards, it shows the design features that iVR experiences must include to meet the desired conditions of visualization and interactivity. It distinguishes between locomotion and interaction systems and how these impact different types of iVR experiences. Visualization factors are common to all types of iVR experiences, although their impact is lower in passive ones and higher in the interactive ones. Lastly, the type of HMD and DoF in which these experiences could be reproduced are indicated.

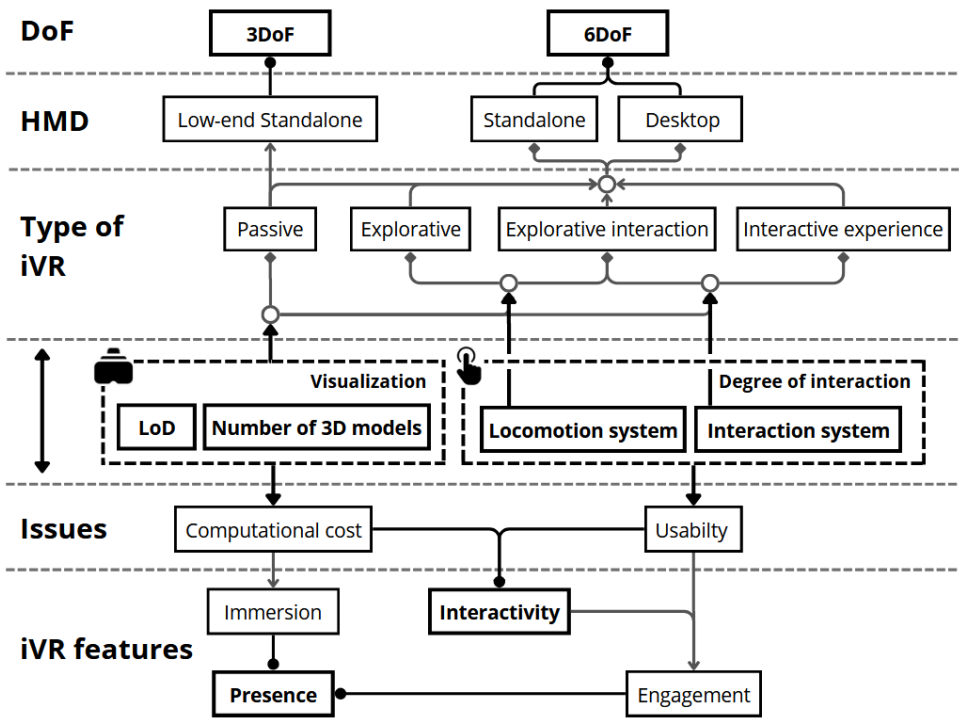


Figure 5. Conceptual framework of design factors in iVR

1.2 iVR and CH reconstruction

Virtual reconstruction of CH has emerged as one of the most rapidly expanding areas of iVR research, alongside other domains such as education and healthcare (J. Zhang et al., 2024). This development is driven, among other factors, by the fact that iVR provides the only means of experiencing vanished CH in first person (Ries &

Schwan, 2023). Extensive research has been conducted on virtual CH reconstruction, ranging from low-immersive VR (Forte & Siliotti, 1997) with pioneering projects such as Rome Reborn, which digitally reconstructed the city of Rome during the Imperial period (Guidi et al., 2007).

The virtual reconstruction of CH falls within the area of virtual archaeology, which refers to the use of digital technologies for CH research (Reilly, 1991). It encompasses various practices, including digitization, reconstruction, and simulation. The term reconstruction generally refers to the digital creation of a real element. However, within the area of virtual archaeology, while this definition may also apply, it is more commonly understood as the digital recreation or restoration of a real element that has been altered, deteriorated, or destroyed (Ferdani et al., 2020). Although, strictly speaking, elements that have disappeared cannot be considered CH, this terminology enjoys broad academic consensus (Forum Internacional de Arqueología Virtual, 2012).

Therefore, the virtual reconstruction of CH is a discipline that is not exclusively technological but is rooted in virtual archaeology. Thus, it must meet certain requirements to be properly implemented to iVR, as discussed in *Section 1.2.1*. In this regard, *Section 1.2.2* addresses the creation of 3D models to achieve proper visualization and presence in iVR, while *Section 1.2.3* focuses on their design to ensure the implementation of appropriate interactivity.

1.2.1 CH reconstructions requirements

The most widely recognized best-practice frameworks are the London Charter (Denard, 2012), later complemented by the Seville Principles (Forum Internacional de Arqueología Virtual, 2012). These documents define the standards that must be followed when developing CH reconstruction. The guidelines can be grouped into two main areas: methodological and technological. The methodological area can be further divided into principles concerning transparency, rigor, and interdisciplinarity. The technological area, in turn, encompasses principles related to the application of technology and sustainability. The following paragraphs elaborate on these concepts in greater detail.

The methodological area encompasses principles related to the quality of the resources employed in the reconstruction, the transparency of the process, and the integration of multiple disciplines throughout its development:

- *Transparency and rigor:* Virtual reconstructions of CH must be thoroughly documented, relying on solid and reliable historical and archaeological sources. Furthermore, the reconstruction process must be transparent, clearly indicating the degree of evidence supporting each assumption, and

reproducible by other researchers (London Charter principles 3 and 4; Sevilla Principles 4, 5 and 7).

- *Interdisciplinarity*: Given the hybrid nature of this research area, which combines humanistic and technical studies, the involvement of professionals from both domains is essential. CH reconstruction is a comprehensive process in which one area should not replace the other but rather serve as a complement (Sevilla Principles 1 and 3).

The technological area encompasses principles related to the use and application of technology in the reconstruction process and in the dissemination of results, as well as the sustainability of these practices:

- *Application of technology*: The outcomes of the reconstruction must be disseminated through the most appropriate technological medium, considering the target audience and, whenever possible, with educational purposes. The design and technical features of the chosen application should be adapted to these requirements, making use of different design patterns or LoDs (London Charter principle 6; Sevilla Principles 2 and 8).
- *Sustainability*: The reconstruction process and its technological applications should be efficient in both economic and computational terms, employing the fewest resources possible while ensuring long-term durability. In this regard, a technological resource should only be employed if it is the most suitable tool for achieving the intended objective (London Charter principles 2 and 5; Sevilla Principle 6).

1.2.2 CH visualization and 3D model generation

The visualization of CH is a critical aspect, as it not only affects the sense of presence in iVR experiences, but a highly detailed 3D model also allows for more accurate representation of CH (Pietroni & Ferdani, 2021). The virtual reconstruction of CH requires creating an asset that has been lost or severely degraded, and therefore typically relies on polygonal 3D modeling techniques due to its capacity to generate 3D models from scratch, previously described in *Section 1.1.3*. However, to ensure a high historical and archeological fidelity, this technique is usually combined, whenever possible, with data acquisition systems of real assets such as photogrammetry (Mendoza et al., 2023); as well as the historical documentation.

Photogrammetry enables the straightforward creation of 3D models from an image dataset through the *Structure from Motion* process: in brief, vertices of the 3D model are calculated through triangulation of correspondences in the images, and these points are then connected to form polygons. Finally, the images are projected onto the geometry to generate the model's material (Remondino & El-Hakim, 2006).

Figure 6 illustrates this process: through the correspondences (p) between the image captured by camera 0 and the images taken from other cameras moving around the object, it is possible to detect the feature points that enable the digital reconstruction of the object.

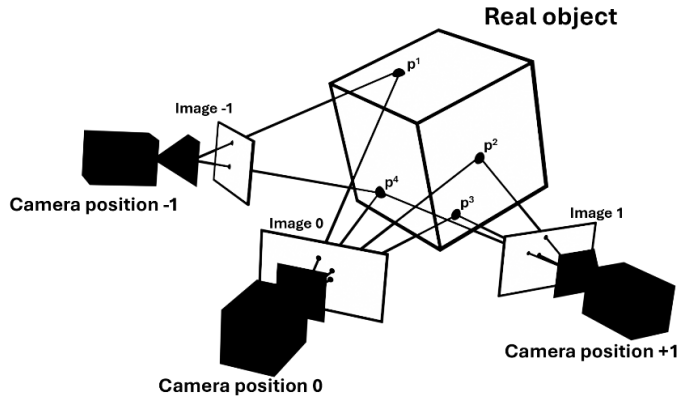


Figure 6. Operation of the Structure from Motion process for the generation of 3D models

The use of 3D model generation techniques from data acquisition methods, such as photogrammetry, and from scratch, such as 3D modeling, offers advantages and limitations that must be considered to achieve optimal visualization.

Although photogrammetry allows capturing real CH assets straightforward to create 3D models, it faces two major limitations: 1) the computational load of the 3D models is excessive, requiring optimization processes; and 2) since the technique is based on image datasets, it can only be applied to existing objects, making it necessary to combine it with polygonal 3D modeling to achieve a CH reconstruction. Furthermore, 3D modeling allows creating elements that have been lost with better optimization, but its use is more complex and requires greater expertise, especially when dealing with interactive 3D models such as virtual agents.

Figure 7 shows the difference in the application of data acquisition and 3D modeling techniques in a virtual reconstruction of CH. On the left side of the image, a partially lost CH asset is presented, while on the right side a completely lost one is shown. In the first case, a data acquisition technique such as photogrammetry can be used to capture its current state, but it must be complemented with a technique like 3D modeling to generate the missing parts. In the case of the completely lost asset, it must be created entirely through 3D modeling, as no remains exist. In the lower-right corner, a table summarizes the advantages and limitations of these two techniques.

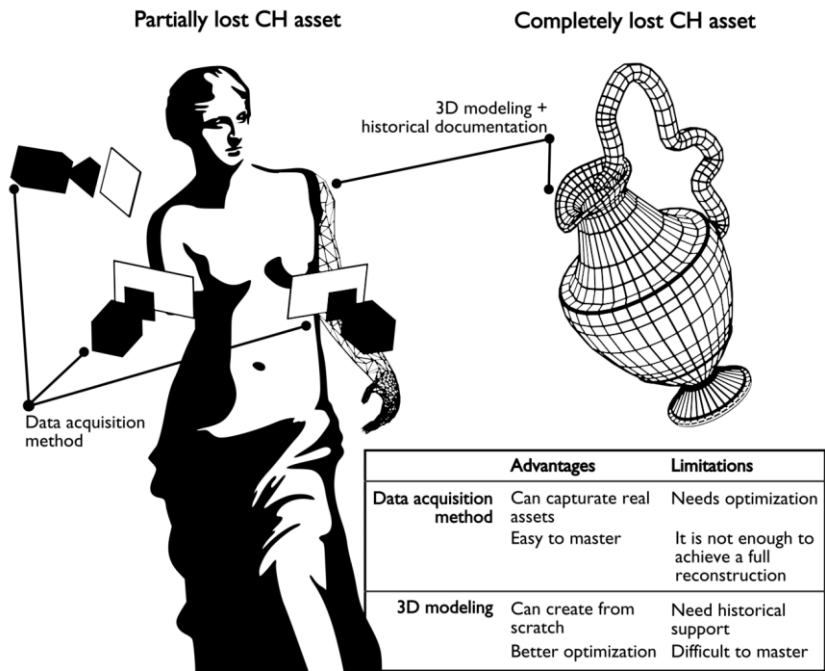


Figure 7. Example of the application of data acquisition and 3D modeling techniques in the reconstruction of a CH asset. In the lower-right corner, a table shows the advantages and limitations of these techniques

1.2.3 iVR design for the dissemination of CH reconstructions

The use of iVR on its own is not inherently beneficial for the dissemination of CH reconstructions (Wang et al., 2025). To achieve this purpose, the application must follow the aforementioned principles and be aligned with an iVR design that effectively implements interactivity. Furthermore, the development of iVR experiences is resource-intensive requiring a carefully managed process. This is particularly relevant given the interdisciplinary nature of the research area, which can hinder the development of reconstructions and iVR experiences due to gaps in technical expertise.

The design and development process of an iVR experience is typically divided into three phases (Horvat et al., 2022): Preparation, Execution, and Post-processing. *Figure 8* provides a phase-based summary of the design and implementation of an iVR experience focused on the dissemination of CH reconstructions. In addition to these specific guidelines for the dissemination of CH reconstructions, it is also important to consider the various key factors in designing an iVR experience, displayed in *Figure 5*. The following paragraphs present these phases in greater detail.

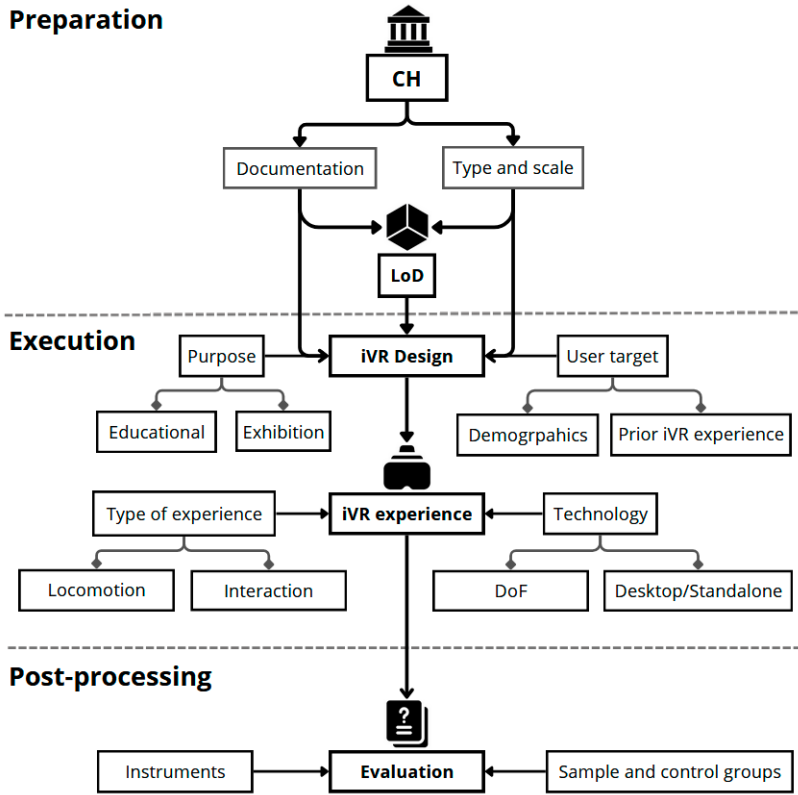


Figure 8. Flowchart for the design and implementation of an iVR experience for the dissemination of CH reconstructions

Preparation: In this phase, it is necessary to consider the CH asset and carry out its reconstruction in order to subsequently design an appropriate iVR experience. The key aspects of this phase are:

- *Type and scale of the CH asset* can range from small-sized sculpture to an entire city. This factor is typically linked to the overall project dimensions, as larger assets usually require greater technical, human, and economic resources for their development (Münster, 2022).
- *State of preservation and documentation* is conditioned by the level of preservation and the quality of available documentation. A CH asset with limited documentation necessitates filling more gaps in the reconstruction hypotheses (Wang et al., 2025), which can influence aspects such as the temporal setting of the reconstruction and the visibility of its various components.
- *LoD* is crucial for virtual reconstructions of CH, as higher LoD improves accuracy and immersion in iVR. However, LoD depends not only on technical factors, but also on the scale, type, preservation state, and available

documentation of the CH. Maintaining a high LoD in a large-scale 3D model demands greater resources a higher degree of conjecture. Furthermore, although photogrammetry as a method for capture and documentation produces highly reliable 3D models with high LoD, the significant computational cost of these models necessitates a more thorough optimization process to ensure efficient resource management.

Execution: In this phase, the focus is on determining how to apply iVR technology to CH reconstruction. It is essential to consider precisely what aspects of the CH are intended to be highlighted through the iVR experience and the target audience. To achieve this, the following questions should be addressed:

- *What is the purpose of the iVR experience?* The type and design of an iVR experience can vary significantly depending on its application. For instance, in educational contexts, factors such interaction and gamification must be considered (Faust, 2021), whereas in exhibitions aimed at the general public, aspects like ease of use and session duration are critical (Vlahovic et al., 2022).
- *Which iVR technology is most suitable for showcasing reconstructed CH?* There are different iVR technologies that vary in terms of functionality, portability, and cost. The first decision involves choosing between 3DoF and 6DoF technology. The former allows iVR experiences with no limit on LoD and lower cost, but at the expense of reduced interactivity and presence. 6DoF experiences greatly enhances interaction possibilities and the sense of presence but requires higher development costs and more complex LoD management, usually through optimization (Chai & Li, 2022). It is also necessary to consider the type of HMD. Desktop devices offer fewer computational limitations but are more expensive and are less comfortable for the user. Standalone devices provide greater comfort and portability, but the development of iVR experiences is more complex due to their higher computational constraints (Checa & Alaguero, 2024).
- *What iVR experience design should be implemented to effectively reach the target audience?* Demographic factors such as age or prior iVR experience can significantly influence the design of an iVR experience and may lead to usability issues. Based on these factors, different design solutions can be implemented, including different types of iVR experiences, tailored controls, or the use of virtual agents, which can greatly improve engagement in iVR.

Post-processing: This phase involves the evaluation of iVR experiences. Assessment processes are an essential component of any research. Previous studies have observed that iVR experiences in CH dissemination typically receive limited evaluation (Tsita & Satratzemi, 2018). To achieve widespread acceptance of this

technology in the research area, it is necessary to demonstrate its benefits through robust assessments. In this context, the following factors must be carefully considered:

- *Use of control groups and sample size* must be adequate to measure the experiment's variables. For experimental validity, a control group is necessary to compare the evaluated variables (Richard E. Mayer, 2014). Likewise, each group within the sample should include at least 20 participants to obtain statistically significant results.
- *Robustness of evaluation techniques and instruments* must be suitable to ensure reliable results. Most studies rely only on post-experience questionnaires or user observation. The use of more complex evaluation systems, such as pre-assessments or data collection during the iVR experience, can be beneficial for obtaining more reliable results (Martinez et al., 2021). In this regard, advanced data collection instruments such as biosensors (Guillen-Sanz et al., 2024) or analysis techniques like Machine Learning can be highly useful tools to enhance the quality of results.

1.3 Advantages of iVR for the dissemination of CH reconstructions

iVR is the most common technology that allows first-person visualization and interaction with lost or degraded CH, making it a way of experiencing many heritage sites (Ries & Schwan, 2023). Therefore, most of its advantages arise from this characteristic. These are summarized in *Table 1* and discussed in detail below:

- *Learning and research*: Virtual reconstructions of CH allow for direct visualization of archaeological hypotheses (Pietroni & Ferdani, 2021). Their use enables greater contextualization of the CH and its surroundings. Additionally, immersive visualization enhances spatial learning (Checa & Bustillo, 2020b).
- *Engagement*: The use of iVR improves engagement through immersive visualization and interaction (Newman et al., 2022). This technology can further increase engagement by incorporating game elements or gamification, narratives, or interactive characters as virtual agents.
- *Dissemination*: iVR enhances the cultural and touristic value of CH by offering highly engaging immersive experiences that help to disseminate historical knowledge (Puig et al., 2020). In recent years, iVR has been tested in museums, demonstrating its potential for dissemination and achieving significant results due to its remote accessibility and increased engagement (Yang et al., 2024).

- *Accessibility:* iVR facilitates access to locations that are otherwise inaccessible, dangerous, fragile, or destroyed, thereby democratizing access to CH. This advantage is particularly relevant for individuals with disabilities, who face greater challenges in accessing such heritage sites (Gatto et al., 2025).
- *Preservation:* The use of technologies such as iVR reduces the handling of real CH assets thanks to digitization, both for study purposes and during visits (Liritzis et al., 2015). Moreover, the process of generating virtual reconstructions produces a large amount of valuable documentation and high-quality digital replicas.

Table 1. Advantages of iVR for CH dissemination

LEARNING AND RESEARCH	iVR offers first-person view that improve spatial understanding
ENGAGEMENT	iVR increases user engagement and motivation via interactivity
DISSEMINATION	iVR fosters appreciation of CH through immersive experiences
ACCESSIBILITY	iVR enables virtual access to hazardous or inaccessible sites
PRESERVATION	iVR minimizes handling of CH artifacts while producing useful documentation

1.4. Limitations of iVR for the dissemination of CH reconstructions

Despite the popularity of iVR in CH reconstruction research, it also faces several limitations that must be addressed for its widespread adoption (Wang et al., 2025). These limitations arise both from factors inherent to virtual CH reconstruction and from general constraints of iVR experiences. These are summarized in *Table 2* and discussed in detail below:

- *User Experience:* iVR experiences in CH reconstruction are typically aimed at a broad audience, especially when intended for dissemination purposes. Designing an iVR experience for this type of audience requires a polished user experience adaptable to users with diverse characteristics, such as age and prior iVR experience. Factors such as the experience design and controls must be carefully calibrated to ensure a pleasant user experience (Kim et al., 2020).
- *LoD:* CH reconstructions generally require a high LoD to accurately represent the CH. This is a challenging factor to manage, as it not only presents technical difficulties, but can also create a false sense of certainty;

therefore, reconstructions must be thoroughly documented (Pietroni & Ferdani, 2021).

- *Technical limitations:* In general, iVR experiences face hardware and software constraints, such as LoD management, product cost, and available movement space. Overcoming these limitations requires technical expertise and budget. Poor management can result in cybersickness or discomfort (Souchet et al., 2023).
- *Complexity of data collection:* This is a critical aspect for advancing research in CH and iVR. However, implementing complex techniques is challenging, especially in public environments such as museums or exhibitions (Vlahovic et al., 2022). Difficulties arise not only in conducting multi-phase evaluations but also in implementing more invasive and sophisticated data collection methods, such as biosensors.
- *Digital Preservation:* Storing and reusing files can pose a risk, as formats and technology advance rapidly. This phenomenon may render much work obsolete (Amico & Felicetti, 2024).
- *Interdisciplinarity:* Creating a CH reconstruction for iVR requires the integration of historical and technological disciplines which can lead to gaps in technical knowledge that hinder development and exacerbate the aforementioned limitations (Münster & Terras, 2020).
- *Economic costs:* In general, the research and development of iVR experiences is a costly process, representing a significant limitation in CH research (Anderson et al., 2010).

Table 2. *Limitations of iVR for CH dissemination*

USER EXPERIENCE	iVR needs a UX that supports diverse users and accessibility
LEVEL OF DETAIL	CH reconstructions require a high LoD difficult to manage
TECHNICAL LIMITATIONS	iVR involves technical limitations that require expert workers
COMPLEXITY OF DATA COLLECTION	Public iVR experiences face time and control limitations
DIGITAL PRESERVATION	File storage and reuse become difficult as technology evolves
INTERDISCIPLINARITY	iVR development requires technical and humanistic experts
ECONOMIC COSTS	Research and development costs are high

MOTIVATIONS AND GOALS

Despite the popularity of virtual CH reconstruction in iVR, research in this area is in many respects less mature compared to its application in other areas such as medicine or engineering (Angra et al., 2025). Due to its emergence, the use of iVR and its potential impact as a tool for disseminating CH reconstructions remains undetermined. Therefore, it is essential to understand its potential to optimize it, providing tools and guidelines to support the development of research in this area.

Although various limitations still pose challenges to the widespread adoption of iVR in CH, this thesis focuses on those that can be addressed through optimization of technology and design. In particular, this thesis aims to create and evaluate CH reconstructions and iVR experiences that optimize their main features: presence and interactivity. To address this issue, different goals covered in several publications have been defined. These goals aim to address the topic from three perspectives that follow the structure of iVR experience design: *analytical perspective*, through the examination of iVR experiences from the viewpoint of CH (Goal 1); *practical perspective*, through the development of tools and CH reconstructions (Goal 2) and CH iVR experiences (Goal 3); and *evaluative perspective*, through an analysis based on the testing of iVR experiences (Goal 4). These goals are described below:

- **Goal 1:** *The review of iVR for the dissemination of CH reconstructions*, as it serves as a starting point, identifying the gaps in current research on this topic. This goal is relevant to provide a comprehensive understanding of: 1) how virtual reconstructions influence the design of iVR experiences and the benefits they provide; 2) how iVR experiences are designed; 3) how research outcomes are evaluated; and 4) which are the most promising future directions.
- **Goal 2:** *The development of optimized 3D models for CH reconstruction*, given that this factor significantly influences immersion and the sense of presence. Reaching this objective requires a straightforward approach of: 1) addressing the evaluation and the optimization of LoD; and 2) optimizing the creation and development process of 3D models for CH.

- **Goal 3:** *The optimization of iVR experience design*, since this aspect is crucial for enhancing interactivity and engagement in iVR environments. Pursuing this objective entails: 1) designing and evaluating different types of interactions and locomotion systems; and 2) assessing how demographic factors influence design.
- **Goal 4:** *The improvement of iVR experience assessments*, given that it constitutes a key aspect for advancing research. In pursuit of this objective, it is essential to 1) identify the purposes for which they can be optimized; and 2) assess iVR experiences in different contexts to determine how such evaluations should be conducted.

Part II

Results

PREFACE

This part presents the results of this thesis in the form of journal articles, either published or under review at the time of thesis submission. These results are aligned with the goals outlined in *Chapter 2 of Part I*. The bibliography used in the articles presented is included within each article itself and not in the *Bibliography* section of the thesis. The citation system used varies, as it follows the guidelines of each journal. Similarly, the tables and figures contained in results are not listed in the thesis' *List of Tables and Figures*.

This publication establishes the starting point of the thesis conducting a state-of-the-art review that enables a comprehensive understanding of the application of iVR technology for the dissemination of CH reconstructions discussing: 1) the influence of the CH on the reconstructions; 2) the characteristics of CH reconstructions for iVR and how they are developed; 3) the applications of this technology; 4) the design; and 5) the evaluation of iVR experiences for the dissemination of CH reconstructions.

The main outcomes of this study are the *de facto* standard and the most promising gaps in the state-of-the-art, which have shaped a set of future research directions forming the basis of this thesis. The most relevant are: 1) optimizing the development of CH 3D models to achieve high historical accuracy with low computational load and high LoD (enhancing presence); 2) optimizing 6DoF experiences, particularly the implementation of interaction and its adaptation to broader audiences (enhancing interactivity); and 3) improving the evaluation of iVR experiences, especially those conducted in public settings such as museums. This result is aligned with Goal 1. *Table 3* presents the bibliometric data of this publication.

Table 3. Bibliometric data of Result 1

TITLE	A systematic review of virtual 3D reconstructions of Cultural Heritage in immersive Virtual Reality
STATE OF PUBLICATION	Published
JOURNAL	Multimedia Tools and Applications
DATE	2024
JCR	Q2 Computer Science, Software Engineering (2023 release)
DOI	10.1007/s11042-024-18700-3
AUTHORS	Bruno Rodriguez-Garcia, Henar Guillen-Sanz, David Checa, Andres Bustillo
KEYWORDS	Virtual Reality, Cultural Heritage, Head Mounted Display, Virtual Reconstruction, 3D Model

A SYSTEMATIC REVIEW OF VIRTUAL 3D RECONSTRUCTIONS OF CULTURAL HERITAGE IN IMMERSIVE VIRTUAL REALITY

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Abstract. Immersive virtual reality (iVR) devices are increasingly affordable and accessible to consumers. The widespread adoption of this technology for professional training is now finding its way into various other fields. One field that is gaining significant popularity is Cultural Heritage (CH), where iVR enables the reconstruction and exploration of lost heritage. However, an up-to-date systematic review of iVR within this field will be of great benefit. Hence, the present review of 94 papers published between 2013 to 2022 that describe PRISMA methodology on virtual reconstruction of CH for iVR. The aim is to identify the key factors behind the development of these applications and their standards. To do so, a statistical analysis on the following topics was performed: 1) nationality, publication date, and article type; 2) heritage type and its current state of preservation; 3) the area of final application and the features of the reconstructions; 4) the characteristics of the iVR experience; and 5) the assessment of the iVR applications. Finally, a roadmap of best practices is outlined for the virtual reconstruction of CH using iVR and some of the most promising future research lines are outlined.

1. Introduction

Virtual Reality (VR) technology emerged in the 1950s and its early rudimentary experiences have evolved into what is known today as Immersive Virtual Reality (iVR) [1]. Since then, iVR technology has undergone significant development, and is a relevant discipline for society [2]. Early VR technology was primarily restricted to military and research activities [3]. However, new uses for VR emerged over the years, such as education and training [4], as well as the dissemination of Cultural Heritage (CH). Combinations of CH with VR technology began to be explored at around the 1990s [5]. Older VR projects, now known as low-immersive VR, the main feature of which is viewing on conventional screens or other 2D displays [4], differ greatly from the technology of the modern iVR projects. The degree of interaction in their environments, or Virtual Worlds (VW), was minimal, and were far from realistic, mainly due to the limitations imposed by the technology available at the time. Some of the references that compile the low-immersive VR VW applications are the following [6,7,8,9]. Those works include the reconstruction of ancient Roman Pompeii, Edo Castle in Tokyo, and later Rome Reborn [10], within which ancient Rome could be freely explored.

As the years passed, technical limitations were overcome, leading to the development of the Cave Automatic Virtual Environment (CAVE), an iVR system in which the user is surrounded by a large 3D viewing area [11]. Those systems marked the beginning of high-immersive VR, or iVR [4]. Cases of CAVE systems appear in the latest reviews during that initial period of CH applications in VR [5, 9, 12]. Some examples from that period include the serious game “*Gates of Horus*” [13], the reconstruction of the 12th c. Muslim suburb of Sinhaya [14], and the virtual tour of the Mogao Grottos in China [15].

However, the iVR technology that has recently become more popular is the new generation of Head-Mounted Displays (HMDs) [16]. These devices have become more affordable, especially since the launch of the first Oculus Rift development kit (dk1) [4]. The popularization of HMDs is having a great impact on iVR research, increasing the number of cases, as mentioned in several reviews [17,18,19]. Indeed, other technological advances are playing a crucial role in propelling iVR forward. Among these advances are the popularization of development engines specifically designed for iVR, such as Unreal Engine and Unity [20], the affordability of digital scanning software [21], and the availability of accessible scanning devices such as DSLR cameras and 360° cameras [22]. Even the increasingly functional technological innovations of smartphones are advantageous for eXtended reality (XR) technologies, given their broader range of functionalities, such as Augmented Reality (AR) [23], or even iVR [24]. This technological evolution has prompted a diversification of research, leading to other review papers on the implementation of CH with XR in various fields, such as Historic Building Information Modelling (HBIM) [25], Virtual Museums (VMs) [18], Virtual Humans (VHs) [26], and Digital Twins (DT) [27].

However, those latest reviews and others on the same topic, despite advancing and proposing new lines of research, present severe limitations when conceptualizing the state of the art of iVR and the virtual reconstruction of CH. A systematic review of 94 papers on the virtual reconstruction of CH in iVR is therefore presented in this paper, to address the lack of reviews on this topic. An analysis of this field is presented in this review paper, taking into consideration the technological explosion of recent years. Aspects such as experience design, its application in various domains such as museums or education, the utilization of technologies such as photogrammetry and the incorporation of VHs will all be analysed. The chronological structure of the analysis covers the steps involved in creating those sorts of iVR experience. An overview of the review structure, based on the review of Hovart et al. [28], is provided in *Fig. 1*. According to that paper, the design of iVR experiences can be divided into 3 phases: preparation, execution, and post-processing. At each stage of the design of an iVR experience of CH

reconstruction, the most relevant items identified in the review articles were analysed. Each item raised a series of questions that were explored and that structured this review. Firstly, the available CH and the characteristics of the 3D model were analysed in the preparation phase. As iVR is a tool that helps people appreciate CH [29], the type of experience that best fitted the CH in question and its characteristics were subsequently analysed in the execution phase. Finally, the evaluations of the reconstructions were analysed in the post-processing phase.

The structure of this paper is as follows. In *Sect. 2*, a review of related work is conducted, emphasizing the novelty of the study. In *Sect. 3*, the methodology, based on the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines, is described. In *Sect. 4*, the taxonomy used in this review, related to CH and its characteristics, the experience, the iVR design, and the evaluation are all detailed. In *Sect. 5*, the statistical analysis of the sample is broken down and the results obtained are presented in the following subsections: (1) demographics, time evolution, and type of publication; (2) reconstruction period, and heritage type; (3) reconstruction characteristics, and area of application; (4) development and design of the iVR experience; and (5) assessment of the experiences. In *Sect. 6*, the best practices identified in the review are summarized with a statistical analysis and future research lines are discussed through a qualitative analysis. Finally, the main conclusions of the review are explained in *Sect. 7*, answering the questions posed in *Fig. 1*.

2. Related Work

As presented in the *Introduction*, numerous reviews have studied the status of CH and XR from multiple perspectives. XR technologies present powerful tools for heritage visualization [30]. It is moreover an upward moving trend [19]. However, there is currently no review in which the relationship between virtual reconstruction of CH and iVR is comprehensively addressed. Existing reviews have limitations when covering the relationship between XR technologies and the numerous applications of XR in CH, due to the breadth of both concepts. In the following section, some of the reviews conducted on the application of CH to XR will be referenced and explanations given as to why they do not cover the gap addressed in this study.

XR is a term that encompasses various technologies, such as VR or AR [18]. Consequently, many of the reviews of CH applications conducted from this perspective are overly broad, as the topic as a whole is addressed, rather than focusing on a specific technology. Some of these reviews are [20, 23, 31-36]. Moreover, reviews have been developed that, while not specifically addressing the

virtual reconstruction of CH and iVR, delve into closely related topics. However, those reviews often have a relatively limited sample size such as the 32-paper review of serious games in CH [37], or the 42-paper review of VR games in CH [19]. In addition, they are not focused on the topic of virtual reconstruction of CH. Indeed, among those reviews, there are some with a very extensive sample size, but their analyses were specifically focused on cases of virtual reconstruction of CH in iVR with limited sample sizes, such as the 290-paper review on VR for CH [35]. Or the 146-paper review of technologies for the preservation of CH [38], though its analysis of AR/VR only covered 17 papers. Furthermore, reviews of XR in the field of CH tend to be focused on other areas, such as VMs [18, 39], VHs [17, 26], or DT [27], but not on virtual reconstruction. Finally, many of these reviews are not literature reviews [20, 31, 33, 39-41]. Therefore, there is also a gap in this type of review.

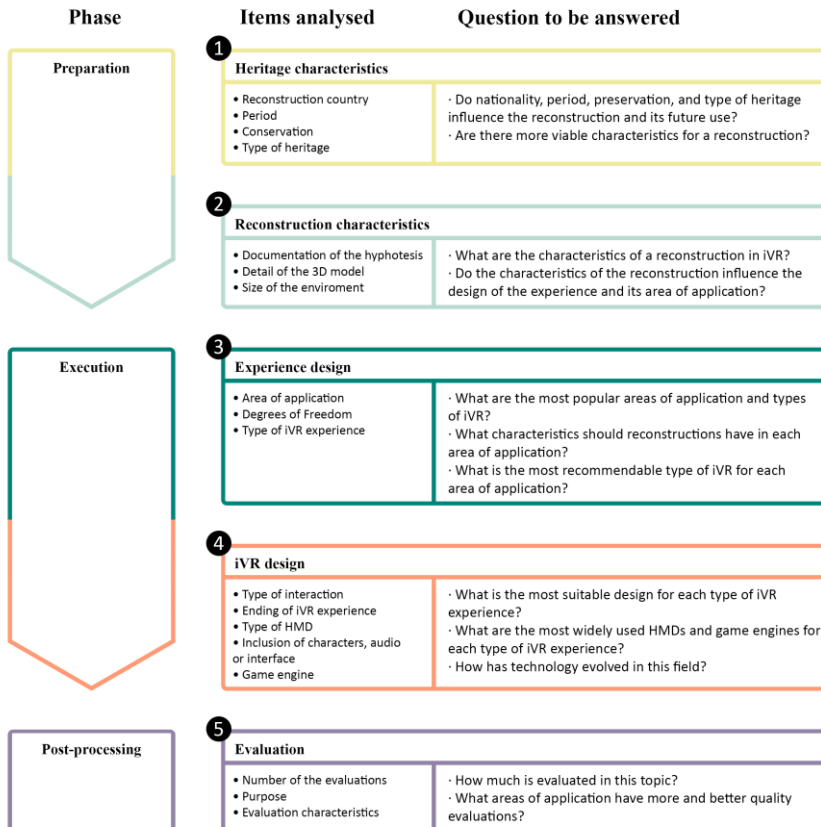


Fig. 1 Summary of the main points covered in the review

Although there has been extensive research on this topic in recent years [42], this investigation has not been specifically focused on the use of virtual reconstruction of CH in iVR. The scenario underscores the need for a literature

review that addresses the relationship between those two topics, to elucidate the current state of the art, its characteristics, and future lines of research. This study addresses that gap by updating the existing bibliography on CH and XR, analyzing the relationship between virtual reconstruction of CH and iVR.

3. Methodology

The PRISMA methodology [43] was followed in this literature review. It enables the transparent explanation of the systematic review process, so that aspects such as the search strategy, eligibility criteria, and the process of selection and analysis can all be easily elucidated. The entire methodological process can be consulted in *Annex I*.

Only 1 search was performed to find all the study cases. The search was *TITLE-ABS-KEY (((virtual AND reality OR vr) OR ((virtual AND reality OR vr) OR headset OR HMD OR head AND mounted AND display)) AND (cultural AND heritage OR CH OR digital AND heritage) OR (reconstruction OR 3d AND model OR virtual AND tour))*. Only articles published between 2013 and 2022 were analysed. The search was run in December 2022 on the Scopus database. In the search process, it was necessary to resort to specific keywords to locate all the cases, without limiting the search to the mandatory appearance of those keywords. Many of the papers with different purposes shared keywords, such as “VR” in articles that reported the use or made no mention of HMDs, or “reconstruction” in 3D reconstruction and photogrammetry papers. Finally, some papers that appeared in the bibliography of the sample were added to the review, in an example of a snowball effect.

Figure 2 depicts the steps of the process following the PRISMA methodology, which left a total of 94 papers [16, 44-136]. The title and the abstract of each paper were read to select the ones to be included and to verify whether they fitted the requirements of the analysis. If the information was not clearly explained in the abstract, a first reading was performed to determine whether to include the paper in the review. Once selected, the papers were analysed on a spreadsheet that was also used for the statistical analyses. This information can be consulted in *Annex II*.

The purpose of the above criterion was to select papers that reported the reconstruction of tangible CH environments visualized through HMDs with iVR systems. If any parameter was not clear in the article, a more in-depth search was performed to locate it; if the data were not found, the article was excluded. The parameters of the exclusion were as follows:

- *The paper was a review, an editorial, or another type of publication that did not explain a case study.* Although articles of this type were excluded, their references were reviewed for inclusion in the sample.

- *The paper does not describe a case of virtual reconstruction of CH.* For this purpose, the experience cannot represent existing CH. In other words, existing heritage reformed at some point in the past was acceptable, even if its original appearance and its current appearance were not alike. In addition, the reconstruction hypothesis must be based on some kind of historical or archaeological documentation.
- *The heritage has no environment.* Only CH with either an environment or an observable or explorable environment was selected. Single objects or collections of objects were removed from the selection. In this way, experiences such as virtual museums were excluded, unless they offered access to complete environments.
- *Intangible heritage.* The reconstructed heritage must be tangible. Intangible heritage cases were accepted, if they also reconstructed the environment and the environment was tangible heritage, so a virtual reconstruction of intangible heritage that included a tangible environment was acceptable.
- *The experience was not iVR with HMD.* In this way all the projects that used CAVE, AR, Mixed Reality (MR) or non-immersive VR with a regular screen were excluded, in order to compare only the most common iVR systems. Also, if a conversion of the 3D model to iVR was planned in the study, but it had yet to be converted, then the paper was also excluded.

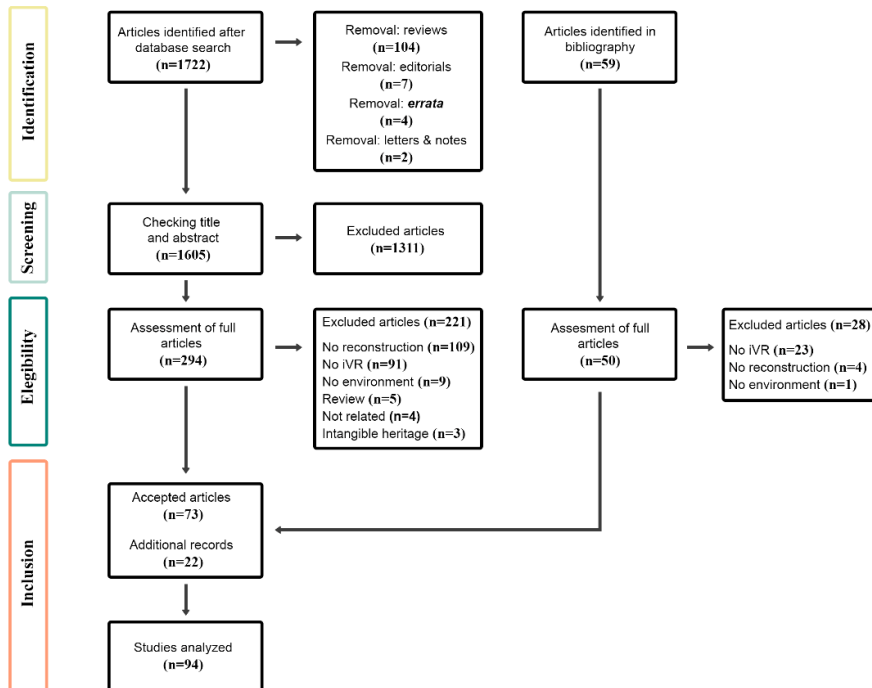


Fig. 2 PRISMA literature analysis diagram of the review

Many parameters were considered in the course of this review, due to the depth of the analysis. So as not to extend the paper unnecessarily, the parameters of each article listed in spreadsheet form can as previously mentioned be consulted in *Annex II*.

4. Taxonomy

In this section, the taxonomy used to analyse iVR experiences and their characteristics are introduced. *Figure 3* provides a summary of the taxonomy, which is presented in chronological order, reflecting the stages involved in creating a virtual reconstruction of CH in iVR, starting from the preparation and ending with the post-processing stage. The following sub-sections therefore describe the taxonomy in accordance with the order proposed in *Fig. 3*: (1) heritage characteristics; (2) reconstruction characteristics; (3) experience design; (4) iVR design; and (5) evaluation.

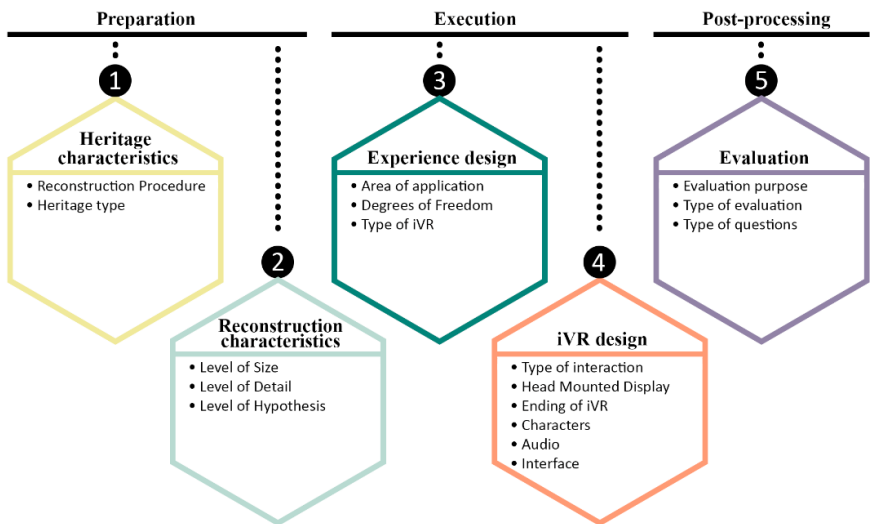


Fig 3 Taxonomies used in the review and chronologically ordered according to the phases of creating a virtual reconstruction of CH for iVR

4.1 Heritage characteristics

When creating a virtual reconstruction of CH, the initial step is to analyse the available heritage [41]. This step is critical, because the CH is the foundation of the iVR experience [29]. Two taxonomic classifications are proposed in this review with which to analyse the heritage characteristics: (1) the first category is the Reconstruction Procedure (RP), which indicates the type of procedure used to

reconstruct the CH, determined by its preservation status. (2) The second taxonomy is the heritage type, taking into consideration its original usage.

Four distinct procedures were proposed in relation to RP. All four procedures varied according to the reconstruction techniques and the current state of the heritage. Each technique is classified as either a 3D-modelling technique or as a digitization (such as photogrammetry or 360° photography). A distinction regarding the state of the heritage was drawn between complete disappearance or scarce remaining traces, and partial preservation of the original appearance or having undergone restauration. The classification used in this paper was based on de Francesco's work [137], in so far as the same techniques were used for the reconstruction, though its complexity was broader, as the current state of the heritage was also compared with Münster's classification [138]. In that taxonomy, reconstruction and digitization of heritage differ, depending on whether human interpretation is required to undertake the reconstruction. Taking this into account, the following RP taxonomy has been created:

- *Virtual reConstruction by 3D modelling (reCon3D)*: 3D modelling is used as the main tool in a heritage that has disappeared or of which few ruins remain. For instance, the virtual reconstruction of the 14th c. Spanish city of Briviesca [128].
- *Virtual reConstruction by digitalization (reConD)*: Photogrammetry, 360° photography or other digitization techniques are used as the main tool in a heritage that has disappeared or of which few ruins remain. For example, the virtual reconstruction of the 4th c. BC Roman Theatre of Miletus, in Turkey [54].
- *Virtual reForm by 3D modelling (reForm3D)*: 3D modelling is used as the main tool in heritage that has undergone few changes or a restoration. For instance, the virtual reconstruction of Ioannina Open Market in the 20th c., in Greece [55].
- *Virtual reForm by digitalization (reFormD)*: Photogrammetry, 360° photography or other digitization techniques have been used as the main tool in a heritage that has undergone few changes or a restoration. For example, the virtual reconstruction of the Spanish city of Burgos in the 20th c [60].

The following taxonomy was used to classify the heritage types. It was based on the types of heritage most frequently found in the review and the classification was based on the original usage of the heritage:

- *Civil heritage*: This category includes heritage designed for civil use, such as theatres, forums, or residences: for instance, the Forum of Augustus in Italy, 1st c. B.C [123].
- *Urban heritage*: This classification includes entire population centres or parts of them. There may be heritage from the other categories within these centres of population, but if the element to be reconstructed is the centre or a part of it, it will be classified in this way. For example, the town of Segeberg in the 17th c. in Germany [91].
- *Sacred heritage*: This category groups sacred or cult heritage, such as churches or mosques, but also Roman temples or other places of worship. For instance, the Temple dedicated to Hera at Paestum in Italy, in the 5th c. B.C [74].
- *Industrial heritage*: This taxonomy includes heritage or elements with industrial use. It includes heritage from before the last industrial revolution, such as neolithic or Roman furnaces. For example, the Power Plant of Piešťany located in 20th c. Slovakia [86].
- *Other*: This category groups different minority types of heritage located in the sample, such as military heritage. For instance, the Sarajevo war tunnel constructed in Bosnia Herzegovina in the 20th c [69].

4.2 Reconstruction characteristics

In this section, the taxonomy of the virtual reconstruction and its characteristics are described. A reconstruction is created on the basis of the heritage characteristics [29]. First, as it is an iVR experience, restrictions on user movements within the environment must be considered. Secondly, as it is a virtual reconstruction, both the detail of the 3D model [139] and the documentation to create a 3D model can vary [41]. Considering the above, three metrics were used to compare the reconstruction characteristics: the Level of Size (LoS) of the environment, the Level of Hypothesis (LoH) of the reconstruction, and the Level of Detail (LoD) of the 3D model. All metrics were rated on a scale of 1 to 5. The parameters were used to analyse the sample in the same way as Koszewski [140] and Münster [141], but with the addition of LoS, as it is an important factor when analyzing environments.

The LoS metric is used to measure the size of the environment. The 360° environments were separated from free roaming iVR environments for accurate evaluation of the size. The 360° environments were marked as such before the metric was applied, and together with the free roaming iVR environments were rated on a scale of 1 to 5, based on their size. *Figure 4* provides a visual comparison of the different environment sizes in relation to the size of a person. Based on those sizes, the following scores for LoS were assigned:

- 360° : is a rendered 360° environment. For instance, the virtual reconstruction of the “Villa con ingresso a protiro” in Italy in the 2nd c. AD [126].
- 1: a small, closed environment. For example, a room, such as the Ducal Chapel of San Ludovico in Parma, Italy in the 19th c. [108].
- 2: a large, closed environment or a closed environment with several spaces. For example, a house with several rooms. For instance, the theatre “Corral de comedies de l’Olivera” in 17th c. Spain [99].
- 3: a small open environment. A single open and delimited space of small size. For example, the Roman theatre of Pausilypon, Italy, built in the 1st c. BC [97].
- 4: a large open environment. A medium-sized open space with different bounded areas. For instance, the Kampung Hulu Mosque with its garden in 18th c. Malaysia [98].
- 5: a very large open environment. A large-sized open space with different bounded areas. For instance, an entire city, such as the 17th c. German city of Stade [112].

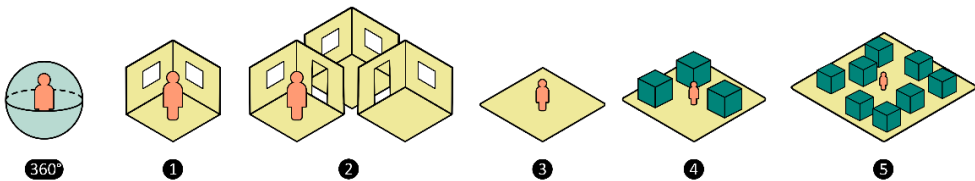


Fig. 4 Examples of the different sizes of environments according to Level of Size (LoS) scores in relation to the size of a person

The LoD is a computer science concept that defines the degree of abstraction of a real object versus its virtual representation [142]. As the level of abstraction decreases, the model object appears more realistic. In this review, the LoD score was based on both its geometrical and radiometrical fidelity. These two parameters have been considered taking into account on the Münster classification of LoD [141]. The final LoD score of the model was obtained by averaging these two features. On the one hand, geometrical fidelity refers to the detail on the surface of the 3D model. On the other hand, radiometrical fidelity refers to the detail in the reproduction of its visual properties. Lighting parameters were not considered as this is a factor outside the 3D model. The degree of angulation of the faces of the 3D model was used to measure geometric fidelity. A lower angle implies greater detail, as it provides more points for creating geometric details [143]. Two factors were considered for the measurement of radiometric fidelity: on one hand, the resolution of the textures, and on the other hand, the quantity of textures per material. Higher texture resolutions imply a higher LoD; likewise, a greater quantity of textures per material suggests

more complex Physical Based Rendering (PBR) materials [144], which implies a higher LoD. In that type of measurement, a more realistic model is therefore considered to have a higher LoD. It is unsuitable for stylized models where realism is not an objective. However, this is not a problem in the context of CH, where virtual reconstructions typically strive for realism [145]. More details on this method can be found in *Annex III*. The score had to be estimated, because the 3D models cited in the papers were inaccessible. The scores ranged from 1 to 5, at intervals of half a point where higher scores indicated higher realism.

Figure 5 displays three examples of LoD assignments to CH models, previously created by the research group. The first image shows the virtual reconstruction of the city of Palacios de la Sierra, Spain, in the 11th c. Its score, 2 out of 5, was due to its simple shapes and textures, indicating a low LoD. The second image displays the virtual reconstruction of the city of Leon, Spain, in the 1st c. BC. The superior geometrical fidelity of the model included details such as doors and chimneys, and different materials, and those and other details may be appreciated, due to its radiometrical fidelity. This model received a score of 3.5 out of 5, indicating a medium LoD. More details about the development of this model are elucidated in another paper [146]. Finally, the third image shows the virtual reconstruction of city of Vitoria, Spain, in the 12th c. In this case, both geometrical and radiometrical fidelity are hyper-realistic, resulting in a score of 5 out of 5, indicating a high LoD.



Fig. 5 Examples of different reconstructions according to Level of Detail (LoD) scores. The first image shows the virtual reconstruction of the city of Burgos, the second of the city of Leon, and the third of the cathedral of Santa María of Vitoria

The LoH, or Level of Information in other papers [2], measures the quality of the historical sources used in the reconstruction. It is a commonly used classification in the field of virtual reconstruction [90]. In this paper, the LoH score was classified on a scale of 1 to 5, along with other features. The following aspects were considered to assign the score. The information sources were reduced to 3 inputs, to simplify the

process and to generate a LoH that could in all cases be comparable: archaeological remains, documentation, and memory. Greater weight was given to primary sources, such as archaeological remains, as opposed to secondary sources, such as graphic and written documentation. Memory was given the lowest score, as it is not an immutable record. The same procedure that Münster [141] and Hauck [147] followed to assign the scores was replicated. The scores varied depending on whether multiple documentary sources were combined, though always with a preference for archaeological remains over documentation, and documentation over memory. On that basis, the following scores for LoH were assigned:

- 1: The source of information was mainly based on the memories of people who knew the heritage.
- 2: The source of information was mostly written or graphic documentation.
- 3: The source of information was mainly written or graphic documentation with the support of the memories of those who knew the heritage.
- 4: The source of information was mostly drawn from archaeological remains.
- 5: The source of information was mainly archaeological remains with the support of written or graphic documentation.

4.3 Experience design

Having obtained the 3D model of the virtual CH reconstruction, an iVR experience can be designed to showcase the reconstructed heritage. This taxonomy can be divided into the following parts: one dedicated to the design of the experience while considering its area of application, and another dedicated to the type of iVR experience. Three taxonomic categories were used in this section: one for the area of application, another for the Degrees of Freedom (DoF) of the experience, and a third for the type of iVR experience.

Münster's classification [138], was used as a basis to classify the area of application. However, a new and frequently observed category in the analysis of the sample was also added -e.g., the Musealization of Marto [32] and Bekele (called Exhibition in his review) [20]- which resulted in the following classification:

- *Preservation*: Although specified in a broader context in the paper of Münster, preservation in the context of this study is associated with iVR experiences that are usually limited to university research with no precisely defined target audience.
- *Musealization*: VR experiences designed to be used in exhibitions or museums.
- *Education*: VR experiences with educational uses or evaluated with students to test their educational potential.

- *Research*: works with the purpose of research within the discipline. They evaluate the virtual reality experience with experts in the discipline to improve some features.

iVR experiences can be categorized based on the DoF of the user's interaction with the VW [148]. There are two types: experiences with 3 degrees of freedom (3DoF) and experiences with 6 degrees of freedom (6DoF). These degrees of freedom determine the user's freedom of movement in the VW.

- *3DoF*: the user can interact with the environment by rotating the view, but the user cannot move around the VW. The 3 degrees correspond to the rotation of the 3 spatial axes.
- *6DoF*: not only can the user rotate the view, but the user can also move around the VW in all directions. This type of movement usually generates a greater sense of immersion. The 6 degrees correspond to the rotation and displacement of the 3 spatial axes.

Among the characteristics of an iVR experience is full user immersion in the VW [149] and interaction with it in a natural way [150]. Hence, Checa's [4] classification was used, based on the range of user interactivity that defines the different types of iVR experiences. The taxonomy is as follows:

- *Passive*: very limited user interactivity and movement, such as 360° environments.
- *Explorative*: free exploration of the virtual environment, although no direct interaction.
- *Explorative interaction*: the user can explore and interact freely with the virtual environment.
- *Interactive experience*: user interaction with the environment, but no free movement within it.

4.4 Immersive Virtual Reality design

Once the area of application and type of iVR experience are determined, other design decisions can be considered. The most important design decisions observed in the sample were as follows: 1) how interaction takes place in iVR; 2) how the experience is ended; 3) the HMD through which it is visualized; 4) the inclusion of characters; 5) the utilization of sound resources; and, 6) the use of interface. The following taxonomies were therefore established.

The taxonomy relating to interactivity was partially adapted from Checa [128] and Boletsis [151], though 2 new types of interaction that are more commonly used in 3DoF experiences were added. The following classification was therefore used:

- *Head movement*: the user can only rotate the point of view through head movement.
- *Point and click*: movement through the environment is based on a teleportation system through previously defined selectable points.
- *Gamepad locomotion*: Movement through the environment is accomplished by controlling a gamepad or keyboard.
- *Room scale*: Movement through the environment is only accomplished by tracking the user's real movement.
- *Teleport locomotion*: Movement through the environment is accomplished by combining the tracking of the user's real movement and a free teleportation system.

The following aspects were taken into account to classify each HMD: 1) whether the HMD is capable of reproducing only 3DoF or also 6DoF experiences; 2) whether it is limited to functioning only when connected to a computer (desktop device) or whether it can run autonomously (standalone device); and 3) whether the tracking system of the HMD is external or internal and how many degrees it covers. The taxonomy was therefore as follows:

- *3DoF desktop*: HMD 3DoF only works connected to a PC, such as Oculus Rift dk1.
- *3DoF standalone*: HMD 3DoF that can work autonomously, in the same way as a cardboard.
- *6DoF 180° desktop external tracking*: HMD 6DoF with external tracking that can capture the user at an angle of approximately 180° and that need a PC, such as Oculus Rift CV1.
- *6DoF 360° desktop external tracking*: HMD 6DoF with external tracking that can capture the user from all angles and that needs to run on a PC, such as HTC Vive.
- *6DoF desktop internal tracking*: HMD 6DoF with internal tracking, which need to run on a PC, such as Oculus Rift S.
- *6DoF standalone internal tracking*: HMD 6DoF with internal tracking, which work independently, such as Oculus Meta Quest 2.

The following taxonomy was also created in relation to the way that the experience was ended, which covered all possible ways of ending the experience in the sample.

- *Free*: the user can end the virtual reality experience at any moment.
- *Time*: there is a time limit to enjoy the experience, once the time is up, the experience ends.

- *Exploration*: it is necessary to explore the entire environment or view all the 360° points to finish the experience.
- *Tasks*: it is necessary to finish one or more tasks to end the experience.

The inclusion of characters was categorized according to the following taxonomy, taking into consideration their method of creation. Rather than considering avatars, representing users, in the taxonomy, only virtual agents, whether interactive or non-interactive, were used [26].

- *Digital*: The characters were digitally created, with techniques such as 3D modelling.
- *Recorded*: The character or characters were real individuals recorded and integrated into the virtual environment.

Regarding the utilization of sound resources, the following taxonomy was formulated, considering the type of sound, its relationship with the virtual world, and its interaction with the user.

- *Ambient*: diegetic sound effects, directly related with the virtual reconstruction and passive in nature. No user action is required for their playback, i.e., sounds of nature.
- *Music*: extradiegetic sound effects, not directly related to the reconstruction and passive in nature. No user action is necessary for playback, i.e., background music.
- *Sound effects*: actively triggered; user action is required for playback, such as grabbing an object.
- *Narration*: this category encompasses all voice sounds, whether conversations or extradiegetic narrations, and whether or not they require user action.

Finally, the taxonomy related to the user interface is described. Thus, its relationship with both the environment and the user has been taken into consideration. The taxonomy is outlined as follows:

- *Panel*: a diegetic and passive user interface. Situated within the virtual reconstruction and operated independently of user input. For instance, a text panel within the environment.
- *Point of Interest (PoI)*: a diegetic and active user interface. Located within the reconstruction, it necessitates user interaction for display. For example, a panel activated by proximity or by pressing a button.
- *Menu*: an extradiegetic user interface. It exists outside the virtual reconstruction, and accessing it requires the use of a pause function or a user-specific action.

4.5 Evaluation

Developers may administer a survey to users, to determine whether the objectives of an experience have been achieved. There are many types of evaluative surveys and tests, varying in terms of their typology, purpose, and timing. Three taxonomic categories were used in this section: one for the purpose of the evaluation, another for the type of the evaluation, and a third for the type of questions that were used.

The purpose of the evaluation has been classified with reference to Chong's taxonomy [35] in the context of VR for CH practices. Additionally, a category based on Chang's study [152] has been included, emphasizing the effect of engagement in iVR. The following taxonomy outlines the purposes of the evaluations that were analysed:

- *Usability and user experience*: its purpose is to assess aspects of usability or user experience, such as satisfaction or presence.
- *Technology or System application*: the motivation behind the evaluation is to compare or to assess the effectiveness of a technological solution.
- *Education/Engagement*: the purpose is focused on evaluating acquired knowledge or interest in knowledge presented in the reconstruction.

In this review, a classification of evaluation types, in accordance with their phases and implementation times, based on the taxonomies of Martinez [153] and Tsita [154], is presented. The following categories describe the types of evaluations found in the sample:

- *Post-evaluation*: the test was administered after completion of the experience.
- *Pre/post-evaluation*: one test before starting the experience and another at the end of the experience.
- *During/Post-evaluation*: the test was administered at the end of the experience, coupled with data collection during the experience.
- *Pre/During/Post-evaluation*: one test was administered before the experience, another at the end of the experience, and data were collected during the experience.
- *No evaluation*: there was no test.

Finally, the following taxonomy was developed to classify the types of questions most commonly used in evaluation questionnaires based on the type of response:

- *Likert*: Responses can only be given to this type of question in the form of numbered options on a scale. It is not necessary to adhere precisely to a Likert scale as long as the options are graduated on a scale.

- *Options*: This type of question only accepts predefined responses, such as yes or no.
- *Open*: The user can respond freely with their own comments.

5. Survey

In this section, the sample analysis and results are presented in the same order as they appear in the previous sections, as shown in *Figure 3*, with an added sub-section on *Data distribution*. Unspecified data have been excluded from the figures to reduce unnecessary clutter. The values may vary slightly between graphics, due to unspecified data and some papers that treated more than one reconstruction or iVR experience.

The internal organization of each subsection will follow the same structure to facilitate the reading of the *Survey section*. Firstly, the order of variable analysis will be explained, following the sequence presented in *Figure 3*. Secondly, each analysis will be conducted in the following internal order: 1) Presentation of the variables and the method of analysis, 2) explanation of the summary figure if available, 3) presentation of the data, and 4) discussion of results. Finally, a summary of the subsection results will be provided at the end.

The *Survey section* is divided into the following sub-sections: 1) *Data distribution*; 2) *Heritage characteristics*; 3) *Reconstruction characteristics and experience design*; 4) *Design of immersive Virtual Reality*; and 5) *Evaluation*.

5.1 Data distribution

Initially, the data pertaining to the articles in the sample will be examined. To do so, an analysis of the year and type of publication will be conducted. Subsequently, the nationalities of the authors and the localization of the reconstructions will be analysed. Finally, the authors' field of expertise and the indexing of the article in Scopus will be scrutinized through a qualitative analysis.

Statistical data on the date and type of publication were analysed. The sample contained 94 publications: journal articles (46%), conference papers (51%), and book chapters (3%). *Figure 6* shows the temporal evolution of the references separated by type of publication. The X-axis shows the year of publication. The Y-axis shows the number of references per year separated into journal articles, conference papers, and book chapters. The number of references has progressively increased since 2013, reaching a peak in 2018. Currently, the discipline is in a state of consolidation and publications are stabilizing. In fact, 2018 was the year with the highest production, which was consistent with the results of other reviews [18, 19, 34, 38]. Furthermore,

the number of journal publications has increased over recent years, which is an indication of maturity. Nevertheless, there were more conference papers and book chapters than journal publications. These data coincided with some [19, 34], though not all of the reviews on the topic [18, 38]. However, there is little difference between these two types of publications. A deeper analysis of the publications reveals that DAACH - Journal of Cultural Heritage and Digital Applications in Archaeology (n=7), Applied Sciences (n=4), JCH - Journal of Cultural Heritage (n=3), and Archeologia e Calcolatori (n=3) were the preferred journals. In addition, XR Salento (n=7) and CIPA - Symposium on Great Learning and Digital Emotion (n=4) were the preferred conferences.

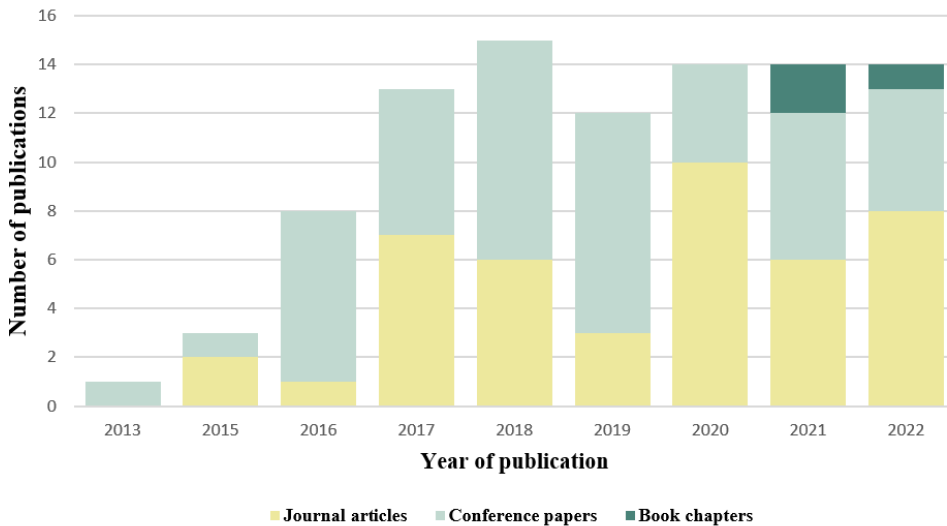


Fig. 6 Number of references and types of publication by year of publication (2013-2022)

The nationality of the first author and the location of the reconstructions were also analysed. Scientific production has mainly been concentrated in Europe (80%), followed by Asia (9%), America (5%), Oceania (5%) and Africa (1%). Moreover, at the continental level, reconstructions were located as follows: Europe (81%), Asia (12%), America (4%), Oceania (2%) and Africa (1%). Most publications were in the following countries: Italy (n=24), Spain (n=17), United Kingdom (n=9), and Germany (n=6). As a result, most of the references referred to the study of reconstructions within either Italy (n=31) or Spain (n=14), particularly those that used Virtual reForms procedures, due in all likelihood to the abundance of Roman remains in these countries. As will be seen in the next section, there is a great abundance of reconstructions throughout the period of Roman antiquity. These results are not unexpected considering that Europe is where most of the assets on the UNESCO World Heritage List are located [30]. Moreover, these results are consistent with the observation of Mendoza [38]

that the first authors of papers on similar topics were invariably based in either Italy or Spain. In any case, Asia stands out in a framework of highly centralized production. It is the second largest producer, almost doubling the production of the third largest, both in terms of the location of the reconstructions. It should be noted that Asia, together with Europe, is the only region in which there is a surplus of reconstructions in relation to actual production. Those results are aligned with the findings of Lucchi [27], which identify Asia as a secondary hub of production in the field of DT and CH.

Finally, an analysis is conducted on the indexing of the article based on Scopus keywords and the field of expertise of the authors. Some articles in the sample lacked a Digital Object Identifier (DOI), so they were excluded from this analysis. *Annex II* provides a list of articles without a DOI. A bibliometric analysis matrix was generated using the Bibliometric software correlations, to scrutinize article indexing [155]. Clusterization and network analysis methods were employed to establish initial correlations. Consequently, *Figure 7* was generated, depicting correlations between the Scopus keywords. These keywords were generated using an algorithm that detects repeated words and phrases forming the titles of the articles. While bibliometric analyses are rooted in data, their visual projection leans towards a qualitative analysis as the interpretation of the graph takes precedence over the raw data. As depicted in *Figure 7*, five clusters were identified, with two markedly larger than the others. These two clusters are denoted in dark green ("*virtual reality*") and orange ("*three-dimensional computer graphics*").

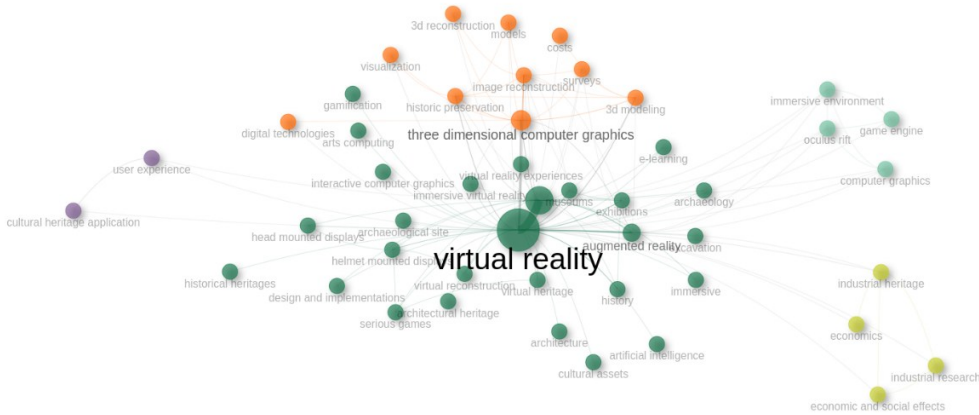


Fig. 7 Matrix of bibliometric data from the selected papers with the Scopus keywords

Interpreting these data reveals a meaningful disparity in the weight of keywords related to technology and virtual VR compared to those associated with CH. The two principal clusters are defined by the keywords "*virtual reality*" and "*three-*

dimensional computer graphics" representing the primary technologies addressed in the analysed articles, one focusing on the creation of 3D models and the other on their visualization in iVR. Conversely, an abundance of keywords related to CH, such as *"museums"*, reflects a growing trend, as highlighted in the introduction. However, these CH-related keywords are subordinate to technological ones, occupying a secondary position in terms of their importance.

Finally, after reviewing the fields of knowledge of the authors, it was observed that most of the articles have a main author from a technical department (n=62), with a secondary author from an history or an archaeology department (n=25). An observation that highlights the interdisciplinary nature of this field according to both Münster [155] and The London Charter [29], in so far as it bridges technical and humanities departments. Nonetheless, similar to the preceding analysis, it is evident that in this discipline, the technical department carries greater significance than the historical department.

In summary, the following conclusions can be drawn. The discipline is in a state of consolidation, having reached its peak production in 2018. These articles are distributed between conference papers and journal articles, with an increasing trend toward publication in journals. Geographically, Europe stands out as the continent with the highest production and the most reconstructions located, with Italy and Spain being prominent within the continent. On the other hand, Asia occupies second position both in terms of production and localization. Lastly, the discipline is clearly interdisciplinary, combining technical and historical disciplines, with a pronounced emphasis on technical aspects.

5.2 Heritage characteristics

The first step in creating a virtual reconstruction of CH is to study the available heritage [29]. The heritage type and its historical period were considered in the analysis of the heritage, its characteristics, and its RP. The first analysis was focused on the relationship between the RP and the period to be reconstructed, the second on the relationship between the heritage type and the period to be reconstructed.

Figure 8 shows the distribution of the sample according to the period of the reconstruction and its RP. The percentage usage of the RPs was as follows: reCon3D (48%), reConD (9%), reForm3D (22%), reFormD (20%). The Y-axis shows two variables: on the one hand, the percentage usage of the RP in each period, graded on the left Y-axis with stacked columns; on the other hand, the total number of cases in each period, plotted with the black line and graded on the vertical Y-axis. The horizontal X-axis shows the period of the reconstruction, grouping the centuries into 7 periods: 1) Neolithic - Bronze Age, from ~7000 BC to 18th c. BC; 2) Iron Age,

from 10th c. BC to 5th c. BC; 3) Roman Republic, from 4th c. BC to 1st c. BC; 4) Roman Empire, from 1st c. BC to 3rd c. AD; 5) High Medieval Period, from 1st c. to 10th c.; 6) Late Medieval Period, from 11th to 15th c.; 7) Modern Age, from 16th to 18th c.; and 8) Contemporary Age, from 19th to 20th c. The arrangement of each reconstruction into historical periods was to facilitate the reading of *Figure 8*, as patterns can be appreciated when differentiating according to the RP. Except for the first three periods (not very representative due to their low number of cases), the use of reCon3D was inversely proportional to the number of reconstructions, since other RPs were used to a greater extent during the periods with more cases. It is an important point, because reCon3D is the majority RP, representing 48% of the cases. However, reCon3D is also the only RP in which no archaeological remains have to be used. However, both ReCon3D and reFormD, both based on digitization, usually employ some remains for digitization, and reForm3D, which also needs some remains to carry out the reconstruction. Regarding the absolute values, it may be observed that the production peaks refer to the periods of the Roman Empire and the Contemporary Age, becoming increasingly frequent towards the present. These periods coincide with those with the lowest relative usage of reCon3D.

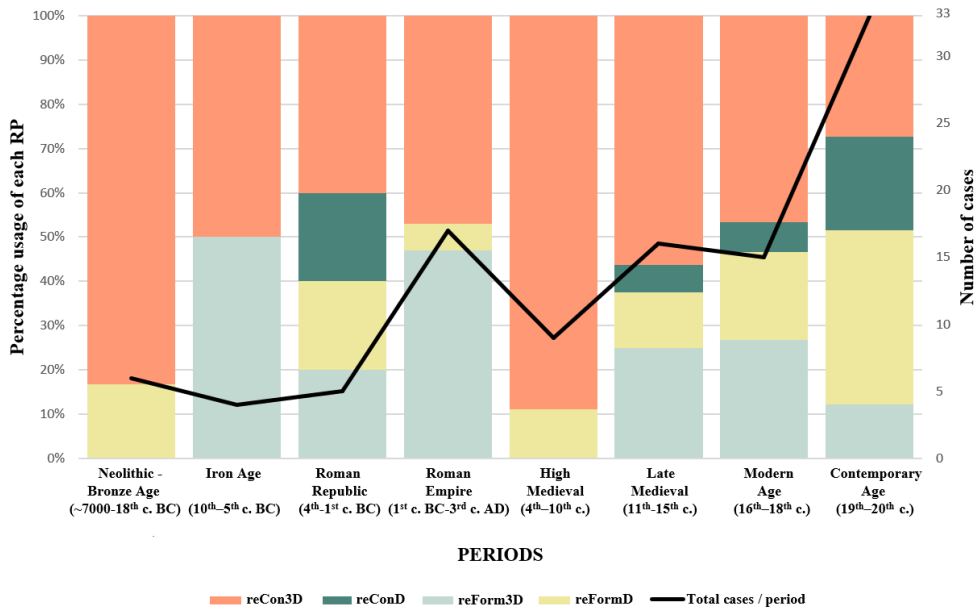


Fig. 8 Distribution of heritage reconstructions by period and by Reconstruction Procedure (RP). Black line shows total number of cases per period

Figure 9 displays the same data as Figure 8, but it separates the sample by types of heritage instead of by RP. In this case, the most frequent types of heritage were Civil Heritage, representing 33% of the cases, followed by Urban Heritage (29%), and

Sacred Heritage (21%). This can be seen in *Figure 9*, where Civil Heritage is concentrated in the period of the Roman Empire and the Modern and Contemporary Age, which are the periods with the highest frequency of cases. Industrial Heritage also shows significant importance in those last two periods. Furthermore, Urban Heritage and Sacred Heritage behave similarly to reCon3D and are frequent in all periods, but especially in those with a lower number of cases, such as Neolithic and Late Medieval periods.

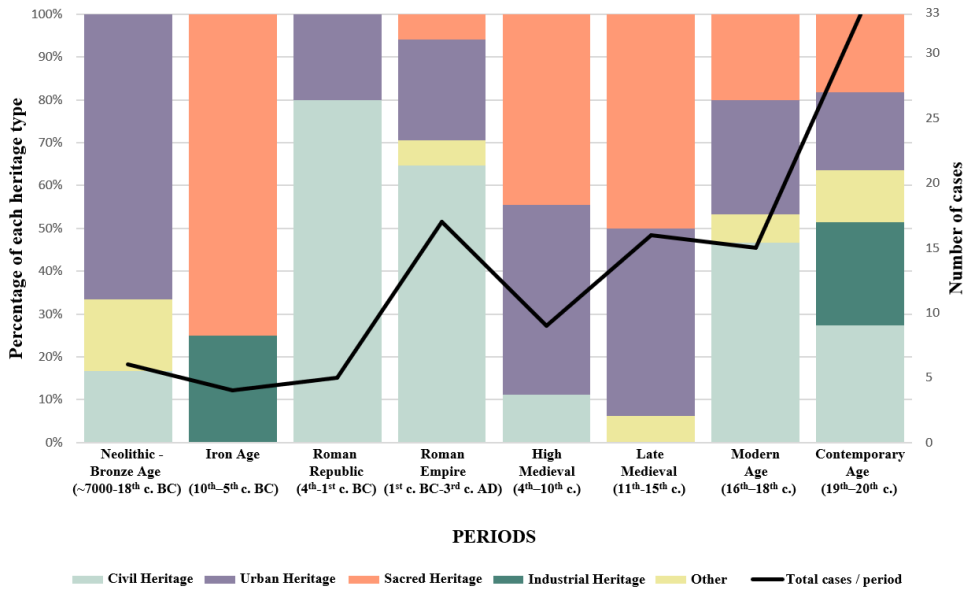


Fig. 9 Distribution of reconstruction cases by period reconstructed and by heritage type. Black line shows total number of cases per period

These results suggest that the heritage characteristics have an influence on the development of virtual reconstructions for iVR. The most frequent periods for reconstruction have been the Roman Empire and the Contemporary Age, which is likely to be due to two factors. Firstly, there are more archaeological remains from these than from other periods, which can be inferred from the RP. RPs requiring archaeological remains are concentrated in these two periods. CH is one of the fields with the greatest weight in digitalization [156]. According to other reviews on similar topics, there are more documentation projects than reconstruction projects [34], and photogrammetry is the preferred data-acquisition system in CH reconstruction [38]. These results are not surprising given the aforementioned factors. Besides, the support from existing heritage makes it easier to create a virtual reconstruction [138]. The second reason for the results, as seen in the previous section, is that Italy and Spain are the countries with the most weight in the

discipline [38]. A reason that might explain the large number of Roman remains and Civil Heritage in the sample that correspond to those historical periods.

5.3 Reconstruction characteristics and experience design

The next step in creating an iVR experience with reconstructed heritage is to design an experience that highlights the value of the available heritage [29]. In this subsection, the reconstruction characteristics and experience design will be analysed together, as they are closely related. First, the most frequent areas of application and their characteristics will be analysed. Secondly, the DoF and the RP will be discussed and, finally, the relationship between that area of application and the type of iVR and DoF.

The areas of application for the experiences are as follows: Preservation (54%), Musealization (30%), Education (12%), and Research (4%). Due to the limited data available for Research and its heterogeneous nature, this area of application has not been included in the results to avoid introducing noise. The low presence of Research in the sample coincides with the observations of Mendoza [38] that AR/VR applications for CH are focused on non-expert users.

The relationship between the characteristics of the reconstructions and the area of application have been considered. *Figure 10* displays the three reconstruction characteristics (LoS, LoD, and LoH) on the Y-axis, each divided according to the areas of application. The X-axis shows the average score for each reconstruction characteristic according to its area of application. Since the use of 360° environments was not scored in the LoS, it will be discussed outside *Figure 10*. The proportion of 360° environments were as follows: Preservation (45%), Musealization (41%), and Education (7%). First, Preservation was the category with the lowest overall scores and that had the most 360° environments. One likely explanation is that these applications are not intended to be tested with end-users and have not left the academic environment. In Musealization, both its relatively low LoS and its high percentage, 41%, of 360° environments stand out. It also had the highest LoD and LoH, a crucial and significant aspect for realism in 3D models [157]. Education was the opposite, with the highest LoS, the lowest number of 360° environments, but the lowest LoD, and its LoH was not prominent.

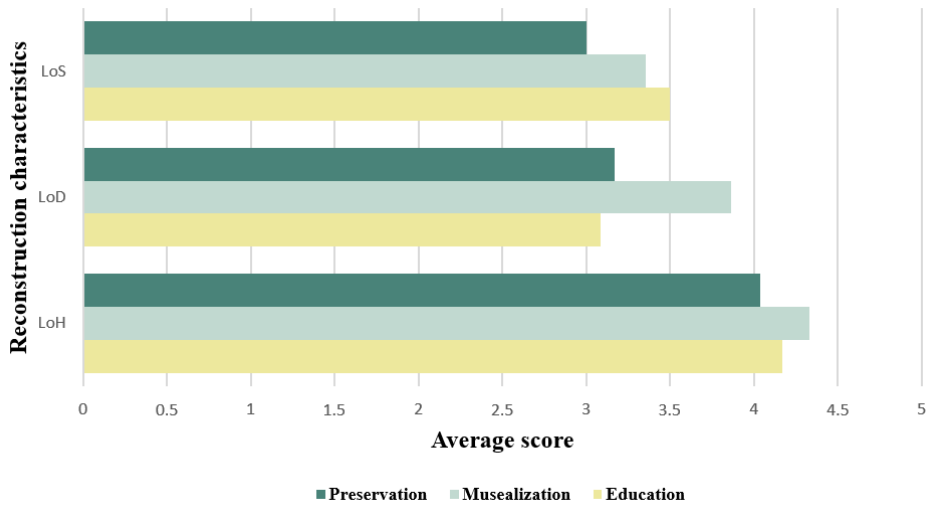


Fig. 10 Average LoD, LoH, and LoS scores for each area of application

The DoF were taken into consideration, to analyse the suitability of these areas of application for an iVR experience. They were furthermore compared with the RP, taking into account the LoS, LoD, and LoH results, considering that the heritage characteristics affected its virtual reconstruction [29]. Analyzing the proportion of reconstruction cases according to DoF, it was observed that 3DoF (32%) was used less than 6DoF (68%), which was the most common type of experience. *Figure 11* shows the percentage of RP and DoF usage by application area on the Y-axis with stacked columns, each column divided into two areas by use of DoF. On the X-axis, each of the areas of application can be seen. The most widely used RP in Preservation was reCon3D, although the use of other RPs was significant, as the proportion was more balanced than in the other areas. Regarding DoF, there was a clear predominance of 6DoF. The most widely used RP in Musealization was reForm3D, an area that stood out because of its low use of reCon3D and high use of the other RP, reFormD, both based on digitization. Regarding the use of DoF, 6DoF was still dominant, but this area showed a greater presence of 3DoF. Finally, the most widely used RP in Education was reCon3D. Similarly, 6DoF was more frequently used than 3DoF.

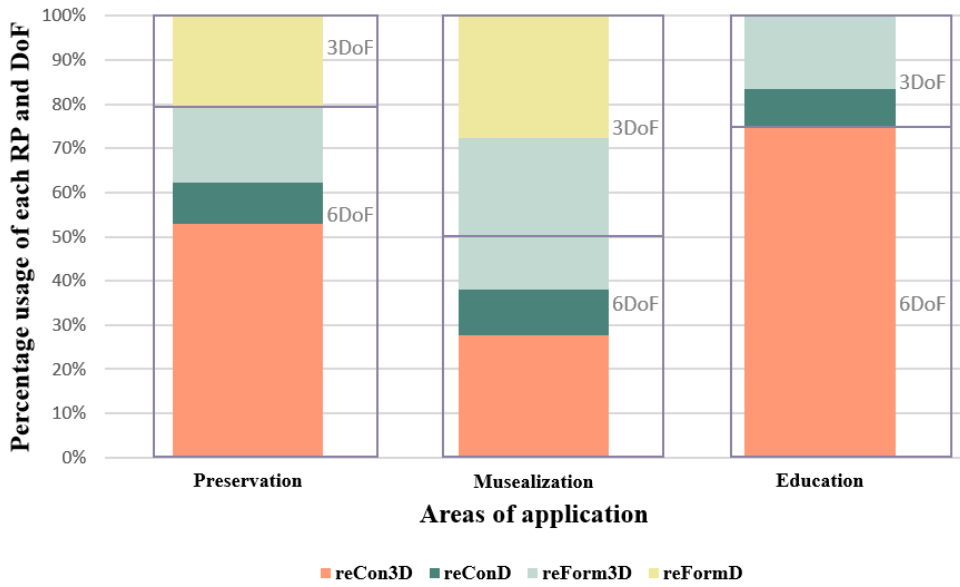


Fig. 11 Percentage usage of RP and DoF by area of application

Based on the above data, the following conclusions can be drawn. Preservation is an area of application where 6DoF predominates, and there is no preferred RP. These data coincide with the general statistics, probably because it is the most general area and was not designed for end-users. Moreover, Musealization has a greater preference for RPs based on digitization, and the use of reCon3D was minor, despite it being the most widely used RP. Additionally, 3DoF can be highlighted within this area. Although its usage was not in excess of 50%, its use was proportionally higher than in the rest of the areas, which is significant given the low use of 3DoF in the sample (32%). Furthermore, Musealization has a proportionally higher number of 360° environments than other areas of application, having almost half of them (45%) despite being a medium-sized area of application (27%). Finally, in Education, reCon3D is the most widely used RP, and 6DoF predominates.

The preference for the use of RP by area of application may be better understood through a comparison of the reconstruction characteristics of the RP by area of application and through their LoS, LoD, and LoH scores. *Figure 12* displays the three reconstructions characteristics (LoS, LoD, and LoH) on the Y-axis, each divided according to the RP. The X-axis shows the average score of the reconstructions according to their RP. Regarding the number of 360° environments, the proportions were as follows: reCon3D (48%), reConD (3%), reForm3D (24%), and reFormD (24%). First, reCon3D showed the highest LoS and a balanced LoH, but the worst LoD. On the other hand, reConD had the second lowest LoS, a good LoD, and the worst LoH.

In turn, reForm3D had the second highest LoS, the best LoD, and an elevated LoH. Finally, reFormD had the worst Los, but a balanced LoD, and the highest LoH.

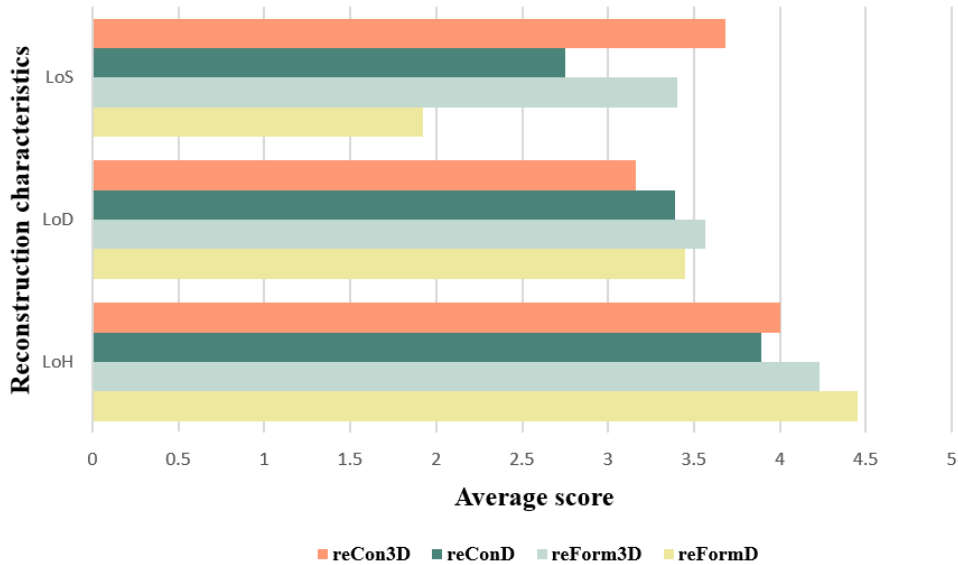


Fig. 12 Average LoS, LoD, and LoH scores for each RP

In the light of those results, the highest LoS and a balanced LoD and LoH can be associated with the RP techniques based on 3D modelling (reCon3D and reForm3D). Conversely, the RP techniques based on digitization (reConD and reFormD) stand out for having the lowest LoS, but a balanced LoH and LoD. Furthermore, these RP techniques accumulate most of the 360° environments. The balance between the RP techniques based on 3D modelling and digitization can be explained by the state of heritage. The RP techniques based on reConstruction (reCon3D and reConD) have worse LoH and LoD. Using those techniques, having a lower LoH is normal since the use of 3D modelling requires filling empty spaces in the LoH [138]. Those based on reForm (reForm3D and reFormD) have a high LoH and better LoD, which assists heritage conservation.

In conclusion, the state of heritage affects the reconstruction characteristics. When fewer remains are preserved the reConstructions are used, LoD and LoH decline, while LoS increases, offering greater flexibility to work directly in a digital 3D environment. Conversely, a greater preservation of CH facilitates reForms and the utilization of digitization techniques, with the resulting improvements to LoD and LoH, due in all likelihood to the ease of generating realistic and accurate models through photogrammetry. These outcomes align with the observations in *Figure 10* and *Figure 11*, where Musealization primarily employs digitization-based

techniques, leading to a lower LoS and a greater emphasis on 360° environments and 3DoF experiences, but a superior LoH and LoD. Conversely, Education focuses on reCon3D, resulting in higher LoS and numerous 6DoF experiences, but yielding poorer outcomes in LoH and LoD. Preservation, on the other hand, showed a less pronounced trend, due to the diversity of available reconstruction techniques and the absence of a clear objective.

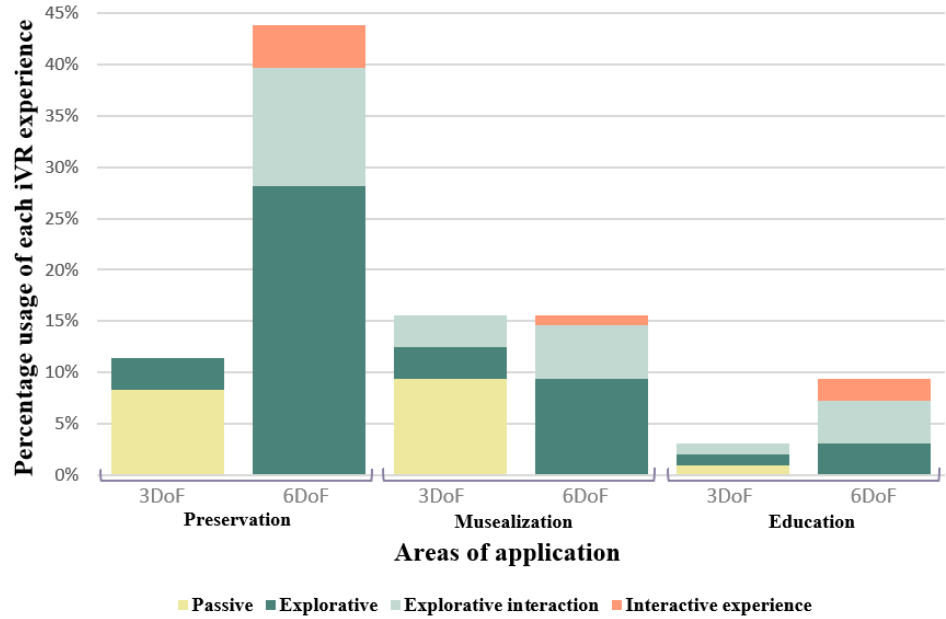


Fig. 13 Percentage usage of different types of iVR by application area and by DoF

The last analysis of this sub-section served to establish the most suitable types of iVR and DoF for each area of application. The amount of iVR types and their relations with the application areas were considered in the analysis. The percentage usage of the iVR experiences were: Passive (18%), Explorative (51%), Explorative interaction (24%), and Interactive experience (7%). *Figure 13* shows the percentage usage of each type of iVR experience by area of application. Each area of application has two columns, the left with the results of 3DoF experiences, and the right the results for 6DoF. On the Y-axis, the percentage usage of each type of iVR experience is shown, and on the X-axis, the application areas are listed. 3DoF experiences are in the minority, but in Musealization experiences, there is a balance with 6DoF, as shown in *Figure 11*. These DoF have a majority use in Passive experiences, exclusive to this DoF. Explorative experiences are also used in this DoF, but mainly for Preservation. Finally, Explorative interaction experiences are used in Musealization and Education, with a greater impact in the latter area where there is a balance

between the 3 types of 3DoF experiences: Explorative, Explorative interaction, and Passive. 6DoF experiences were the most frequently used in all areas except for Musealization. In this DoF, the most frequently used type of experience was Explorative. Explorative interaction and Interactive Experience have some weight in all areas, especially in Education, where the use of Explorative experiences is low. Passive and Explorative types of iVR were the most common according to their DoF, both types of experiences being the least interactive. These results can be contrasted with reviews of other iVR areas where interactive experiences are more prevalent [4].

Regarding the area of application, Preservation is more conducive to 6DoF Explorative experiences. With 3DoF, a clear preference was observed for Passive experiences. Nevertheless, the analysis yielded balanced results in conjunction with the global results, which was in all likelihood due to Preservation, which was the most common area of application with no specific end-user specialization. An equilibrium between 3DoF and 6DoF experiences was evident for Musealization, which was noteworthy given the low usage of 3DoF in the sample. In 3DoF experiences, Passive types were preferred, while in 6DoF, Explorative types were favoured. Both DoFs demonstrated the use of Explorative interaction. Finally, Education showed a strong preference for 6DoF and the most interactive experience types. Even in 3DoF, the use of Passive was minimal. Explorative Interaction was the most frequently used experience type in 6DoF. These results were consistent with the research of Bekele [20], which emphasized that CH educational experiences with XR required interaction. Comparison with reviews of other areas yielded similar results to Checa's review [4] of iVR in education and training.

Summarizing this sub-section, the following conclusions can be drawn. The characteristics of heritage dictate its future area of application, with preferred usage of certain RP types. On the one hand, preferential usage of RP types based on 3D modelling were noted in Preservation, but especially in Education experiences that had high LoS, due to the creative freedom provided by 3D modelling. Interactive iVR types were therefore more frequent in Education [4] where 6DoF predominated and Explorative interaction was the most common experience. In addition, this greater interaction could be used as a pedagogical element in this type of experience [20]. However, they had a low LoH and LoD, which is natural as there were fewer archaeological resources [138], and a high LoD in an educational resource could distract students [158]. On the other hand, RP types based on digitization had a preferred use in Musealization. Their low LoS is aligned with their greater predominance for 3DoF experiences and iVR types with lower levels of interaction. This reduced user freedom may be beneficial in the context of group visits [20]. Moreover, their high LoD and LoH make them suitable for this area, as the high LoD

makes them adequate for end-users due to their visual impact [157], and the LoH makes them useful in Musealization because of its higher historical accuracy. However, they had a low LoS. Finally, Preservation had a less marked profile and a more equitable distribution of RP types, with a predominance of 6DoF and experiences of all types, although Explorative in 6DoF and Passive in 3DoF were more common. As Mendoza noted [38], this less marked profile was probably due to a lack of specialization among the end-users of iVR experiences.

5.4 Design of Immersive Virtual Reality

In this sub-section, the design of the iVR experience will be analysed. Given the significant impact of DoF on the choice of iVR experience type, it is also used to separate the sample. Firstly, the type of interaction will be analysed, followed by the choice of HMD and its relationship with the types of interaction. Thirdly, the way to end the experience will be verified. Subsequently, the use of characters, audio, and interface in the experiences will be analysed. In fifth place, the game engines of each experience are listed and, finally, an explanation will be given of technological developments within this field.

The percentage usage of each type of interaction in the types of iVR experience was analysed, to investigate the relationship between the type of interaction and the type of iVR experience. The percentage usage of each type of interaction was as follows: Head Movement (20%), Point and Click (16%), Gamepad locomotion (17%), Room Scale (10%), and Teleport locomotion (37%). *Figure 14* displays the percentage usage of each type of interaction on the Y-axis, and the types of iVR experience on the X-axis. Each type of iVR experience is divided into two columns, with the left column referring to the 3DoF results, and the right column to the 6DoF results. The Passive experiences were exclusively 3DoF, while the Interactive experiences were exclusively 6DoF. As shown in *Figure 14*, two types of interaction were used in 3DoF: Point and Click for Explorative and Explorative Interaction experiences, and Head Movement for Passive experiences. The 6DoF results were more varied. The explorative 6DoF experiences used Teleport locomotion, Gamepad locomotion, and Room Scale, with a greater preference for Teleport locomotion, the most widely used type of interaction overall. The explorative interaction experiences only used Teleport and Gamepad locomotion, but with a greater use of Teleport locomotion. Finally, Interactive experiences only used Teleport locomotion and Room scale, but in this type of iVR, the most widely used interaction system was Room scale.

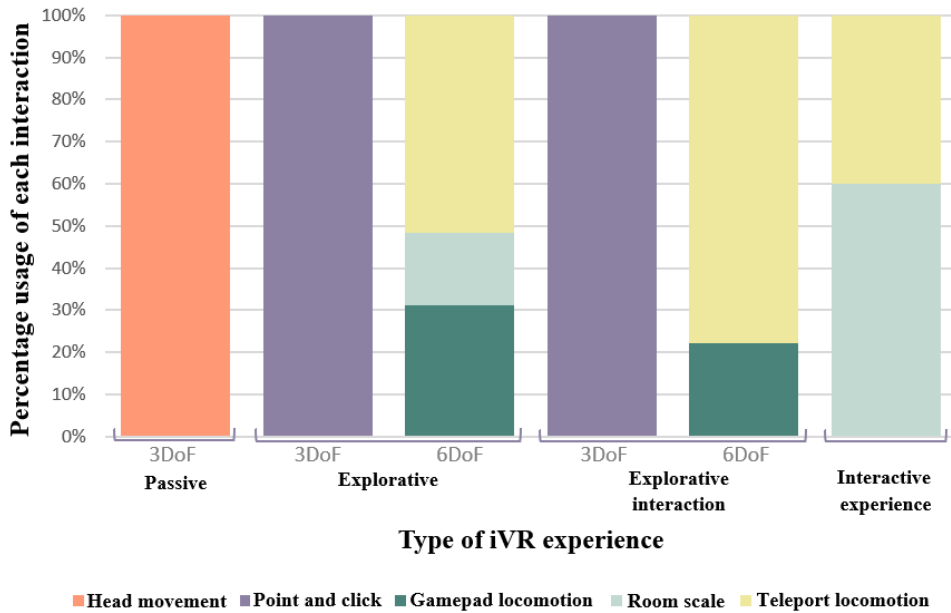


Fig. 14 Percentage usage of interaction type by type of iVR and DoF

These results may be due to the following reasons. The exclusive usage of both Point and Click and Head Movement, the two simplest types of interaction, is standard in 3DoF. Head Movement is the most restrictive, so it is exclusively used in the most limited ‘Passive’ types of experience. Regarding the results of 6DoF, it can be seen that Teleport Locomotion is the most widely used type of interaction. This result is expected, as it has been one of the most common types of locomotion in iVR over recent years, as Prithul pointed out in his teleportation review [159]. Regarding all the iVR 6DoF experiences, Explorative experiences are the most varied interaction types, which may because they are the most common in the earlier years of the study when taxonomies and locomotion systems were more general and less specific [160]. In Explorative interaction, there is an increase in the use of Teleport locomotion, probably because these experiences are more modern and there is a need to teleport over long distances [159]. Regarding Interactive experiences, there is a greater predominance of Room scale and the disappearance of Gamepad locomotion. It is an expected result, as this type of experience is characterized by a lot of interaction within a small space [4]. Therefore, interaction with both a gamepad and a teleportation system make less sense within small spaces [159].

The following point to be studied is HMD usage. To do so, the types of HMDs used during the years under study (2013-2022) were analysed. The percentage usage of HMDs was as follows: 3DoF desktop (6%), 3DoF standalone (23%), 6DoF 180° external tracking (21%), 6DoF 360° external tracking (37%), 6DoF internal tracking

desktop (12%), and 6DoF internal tracking standalone models (1%). *Figure 15* displays on the Y-axis the number of cases and the types of HMDs, while on the X-axis the year of publication of the references are shown. On the one hand, the usage of 3DoF standalone and desktop HMDs is similar throughout all the years, showing no significant evolution. On the other hand, in the first years of analysis (2013-2017), 6DoF 180° external tracking desktop HMDs were widely used, but in 2017 they were being replaced by 6DoF 360° external tracking models in 2017. Those models are the most widely used HMDs, but in recent years, they have been losing ground in favour of 6DoF internal tracking desktop and standalone models.

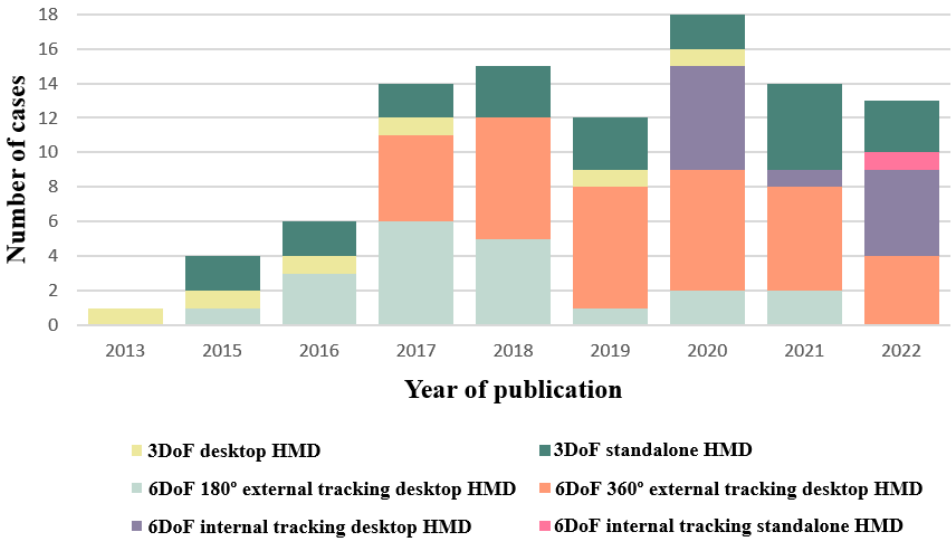


Fig. 15 Development of HMD usage (2013-2022)

3DoF HMDs have been developed least over the 10 years of the study. This finding is reflected in *Figure 14*, which shows the limited variability of 3DoF experiences, due perhaps to their more limited experiences. Regarding 6DoF experiences, the following conclusions can be drawn. There have been three stages in the use of 6DoF HMDs: a first stage dominated by 6DoF 180° external tracking desktop HMDs, a second stage with 6DoF 360° external tracking desktop HMDs (a development that incorporates more complex tracking), and a third stage, that we are currently going through, with more weight placed on 6DoF internal tracking desktop and standalone models. It implies an expected future trend where 6DOF internal tracking desktop and standalone models will replace 6DoF 360° external tracking desktop models as the most widely used HMDs.

The following point is the relation between the chosen HMD and the type of interaction. To do so, the types of HMDs are classified by the type of interaction.

Figure 16 presents the percentage cases of each type of HMD on the Y-axis, and the types of interaction on the X-axis. The types of interaction are separated by their DoF, so Head Movement and Point and Click are exclusive to 3DoF and Teleport Locomotion, Gamepad Locomotion, and Room Scale are exclusive to 6DoF. On the one hand, it can be observed that the 3DoF standalone is the most popular HMD in 3DoF experiences, followed by 6DoF 360° external tracking desktop HMDs. Furthermore, the latter HMD was only used for experiences with a Head Movement system. On the other hand, 6DoF experiences showed more differences. Reviewing the types of HMD, the most widely used were in general also used in 6DoF experiences, in the following order: 6DoF 360° external trackers desktop HMDs, 6DoF 180° external tracking desktop HMDs, and finally 6DoF internal tracking desktop and standalone HMDs. The few cases of 3DoF HMDs for 6DoF experiences were due to outdated experiences and adapted visors. Moving on to the types of interaction, Gamepad locomotion is currently used in the widest variety of HMDs, very probably because it is the most common type of interaction in the first years of the analysis. Room scale follows the majority statistics, with a predominance of 6DoF 360° external tracking desktop models, followed by those with a field of view of 180°. Lastly, Teleport Locomotion was mainly used for 6DoF 360° external tracking desktop models and 6DoF internal tracking desktop and standalone models, with a minor quantity of 6DoF 180° external tracking desktop models.

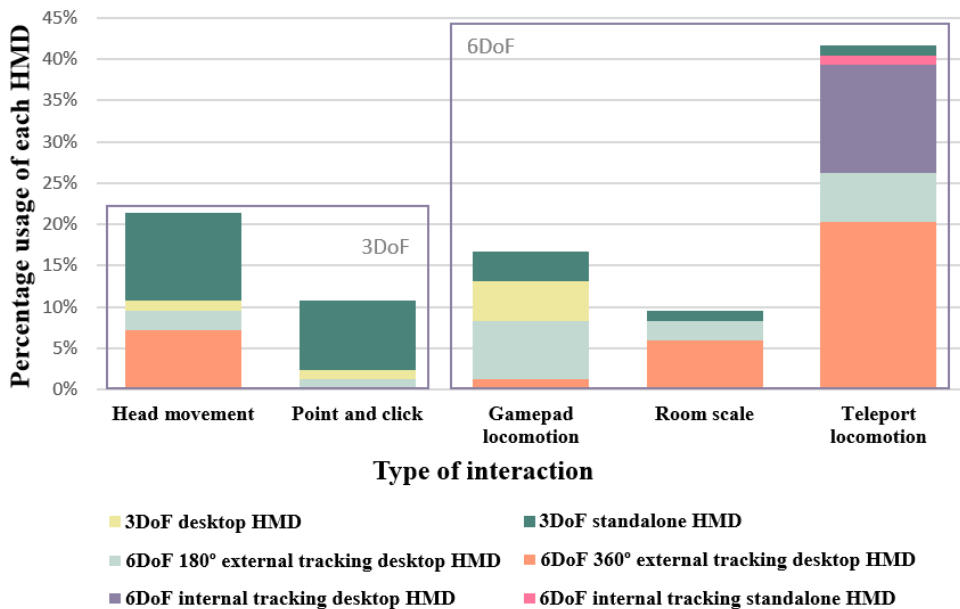


Fig. 16 Usage rates of different types of interaction in relation to type of iVR and DoF

The following conclusions can be drawn from the type of interaction and the HMDs. The most widely used type of HMD in 3DoF is the 3DoF Standalone, followed by 6DoF 360° external tracking desktop HMDs for Head Movement experiences, which is the most common type of movement in 3DoF. The reason for the use of this HMD is probably due to its popularity and it is not surprising that a few HMDs use it for 3DoF experiences. In addition, some equipment, such as eye-tracking sensors, is recommended for that type of Head Movement. With regard to 6DoF, it may first of all be noted that there is no consensus regarding the use of Gamepad locomotion, where all types of movement are used almost interchangeably, probably due to the age of the experiences. Secondly, Room scale is the type of interaction that follows the general statistics, with a majority use of 6DoF 360° external tracking, but being the most unusual type of interaction. Finally, Teleport locomotion is the most widely used type of interaction, making use of the most modern HMDs. This type of interaction is also exclusive to the newer 6DoF internal tracking desktop and standalone HMDs. The use of the most modern HMDs with Teleport locomotion confirms this type of interaction as the most popular locomotion system for 6DoF experiences, echoing the results of Prithul's review on teleportation in iVR [159].

The following analysis was conducted to investigate the different ways of ending the iVR experiences and the type of iVR experience in use. The percentage usage of each type of ending was as follows: Free (62%), Time (8%), Exploration (10%), and Task-related (20%). *Figure 17* displays the percentage usage of each type of ending on the Y-axis, while the X-axis shows the different types of iVR in two columns, displaying the information on the 3DoF and the 6DoF experiences on the left and on the right, respectively. The passive experiences and the interactive experiences were exclusively 3DoF and 6DoF, respectively. No preferred form of ending was evident for Passive 3DoF experiences, with Exploration, Time and Free endings being equally divided. As regards the Explorative experiences, both 3DoF and 6DoF showed a predominantly Free form of ending. However, for Explorative interaction, a greater difference between DoFs can be observed, where Exploration was the more common ending for 3DoF, while Tasks were more frequent for 6DoF, albeit with a still significant presence of Free conclusions in both. Finally, Interactive experiences with 6DoF often had Task-related endings, and less commonly endings with Exploration.

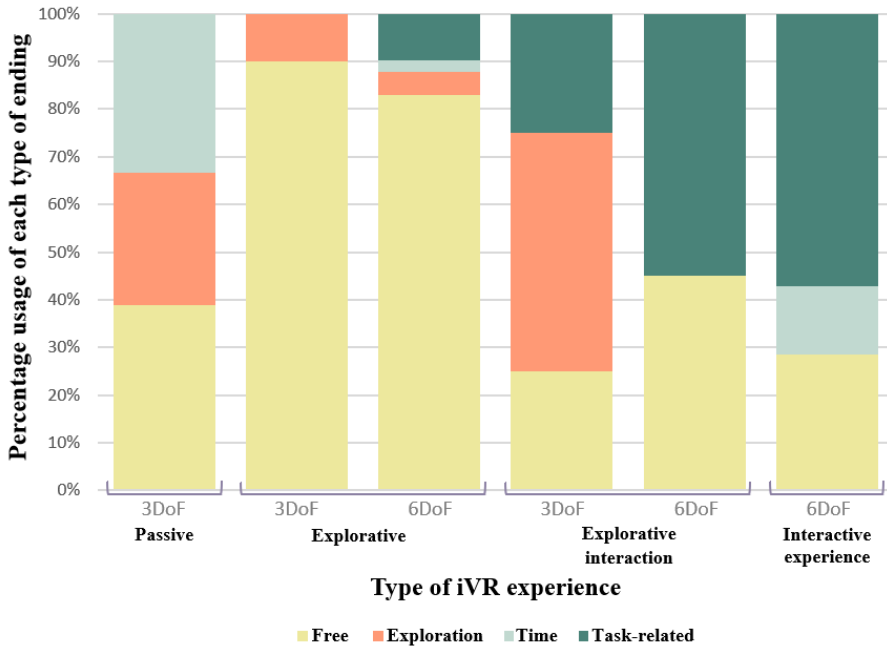


Fig. 17 Percentage usage of each type of ending by type of iVR and DoF

From these observations, certain conclusions can be drawn on the endings of the iVR experiences. While no clear preference could be established for Passive experiences, Task-related endings were excluded, due to the low level of interaction in those mainly 3DoF iVR experiences. Regardless of the DoF, Explorative experiences tended to have Free form endings. Given the limited interactivity of these experiences, it is to be expected, as users are afforded the freedom to explore their environment as they please. As for Explorative interaction, the prevalence of Exploration endings for 3DoF and Task-related endings for 6DoF, can be attributed to the higher degree of interactivity involved in these iVR experiences where both types of endings require active user participation. Finally, the predominance of Task-related endings for Interactive experiences was consistent with the high degree of interactivity present in that type of iVR experience.

The following analysis will be focused on the utilization of characters, audio, and interface in iVR experiences. In that regard, the percentage usage for each element in different types of iVR experiences are considered. Given that many articles lack clear specifications on these concepts, the results should be interpreted as indicative, and the analysis is aimed at providing a general overview. For that reason, unspecified data are included, serving as an indication of their non-inclusion. *Figure 18* depicts the percentage usage on the Y-axis, with each type of VR experience represented on the X-axis. To present the data collectively, the percentage of

character usage in each VR experience is displayed from left to right, followed by the percentage of audio usage, and finally, the interface usage. In *Figure 18*, whether these elements have been used in each iVR experience is presented, without specifying the percentage usage within each category identified in the taxonomy. These data will be discussed in the text, so that *Figure 18* remains clear. Whenever a specific data point is not specified in the article, it is labelled "No inclusion" in *Figure 18*.

Firstly, common patterns will be elucidated, followed by the presentation of individual data for each of the three items. As a general pattern, the inclusion of those elements was observed to increase with the complexity of the iVR experience. There were three exceptions to this pattern, with characters and audio being more common in Passive experiences, and interface inclusion being slightly less common in Interactive experiences. In all, 33% of experiences had characters, of which 28% were Digital and 8% were Recorded. Recorded characters are exclusively used in 3DoF experiences, and predominantly in Passive ones, which explains the higher usage of characters for Passive experiences. Audio formed part of 70% of the reconstructions, of which 36% was Ambient, 20% Narration, 10% Sound effects, and 4% Music, the least common category. Within iVR experiences, there were no clear patterns regarding audio usage, except for Music that was exclusive to Explorative and Explorative interaction iVR experiences. Similar to characters, the extensive use of audio in Passive experiences was attributed to its significant use in 3DoF experiences, where Passive was the type of iVR with the highest audio usage. Finally, interface usage was employed in 59% of experiences, where 24% was PoI, 18% Panel, and 17% Menu. Those percentages remained consistent across types of VR experiences with varying DoF.

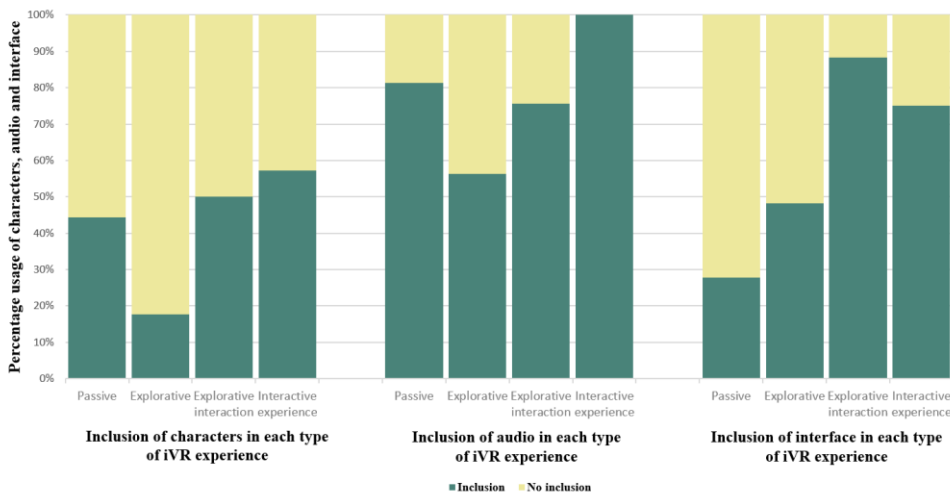


Fig. 18 Percentage usage of characters, audio, and interface by type of iVR experience

The following conclusions were drawn on the basis of the above data. Generally, more complex experiences make greater use of characters, audio, and interface. A conclusion that is not surprising, as higher complexity in the iVR experience requires more elements for interaction and feedback. An exception to that trend was observed in Passive experiences, where the use of characters (exclusively Recorded) and audio was higher. It may be attributed to the non-interactive nature of Passive experiences, as both audio and Recorded characters were pre-recorded resources. Nevertheless, those results should be interpreted as indicative, due to the limited specificity provided in the articles.

Finally, the last analysis of the sub-section was on the type of game engine in the iVR experiences. The usage of each game engine, the LoS and LoD that it achieved, and the specialization of the development teams are considered to achieve this objective. The most widely used development engines were Unity (n=55) and Unreal Engine (n=25). It is no surprise that Unity is the preferred game engine, as it is one of the most widely used in this field [20], as well as within other areas of iVR applications [4]. Nevertheless, the use of Unreal Engine is relatively widespread compared to other areas of iVR applications where it used far less [4]. Something that may be due to the programming simplicity of this game engine, which makes it suitable for multidisciplinary teams [38]. If game engine usage is separated by the field of study of the first author, Unreal Engine has greater usage among history and archaeology specialists. Additionally, an analysis of the reconstruction characteristics revealed that Unreal Engine obtained a better score than Unity in both LoS (3.57 vs 3.03) and LoD (3.88 vs 3.02). These data coincided with the conclusions of other studies that underlined the hyper-realistic results of Unreal [16, 20].

In summary, conclusions regarding the design of 3DoF and 6DoF experiences will be obtained. An analysis of the technological evolution of the topic over the period of analysis (2013-2022) is presented in this sub-section to support the formulation of conclusions. This evolution is depicted in *Figure 19*. The Y-axis displays the number of cases per variable, which, for readability in *Figure 19*, has been divided into three areas, analysing the evolution of the type of VR experience, HMD type, and type of interaction. The X-axis shows the temporal evolution, divided into three triennia to facilitate the analysis and the conclusions: Triennium 1 (2013-2016), Triennium 2 (2017-2019), and Triennium 3 (2020-2022). Although Triennium 1 spans a period of 4 years, it effectively covers three years of analysis, as there were no data available for 2014. These three evolutions were chosen as they were the most technologically relevant among those analysed, clearly demonstrating an evolution. Not all taxonomies within each of these areas are presented; instead, the most relevant ones are included to clarify their evolution. A legend at the end of Triennium 3 displays

the name of each variable alongside its particular line. *Figure 19* is then discussed and analysed in conjunction with the summary of the design analyses of 3DoF and 6DoF iVR experiences.

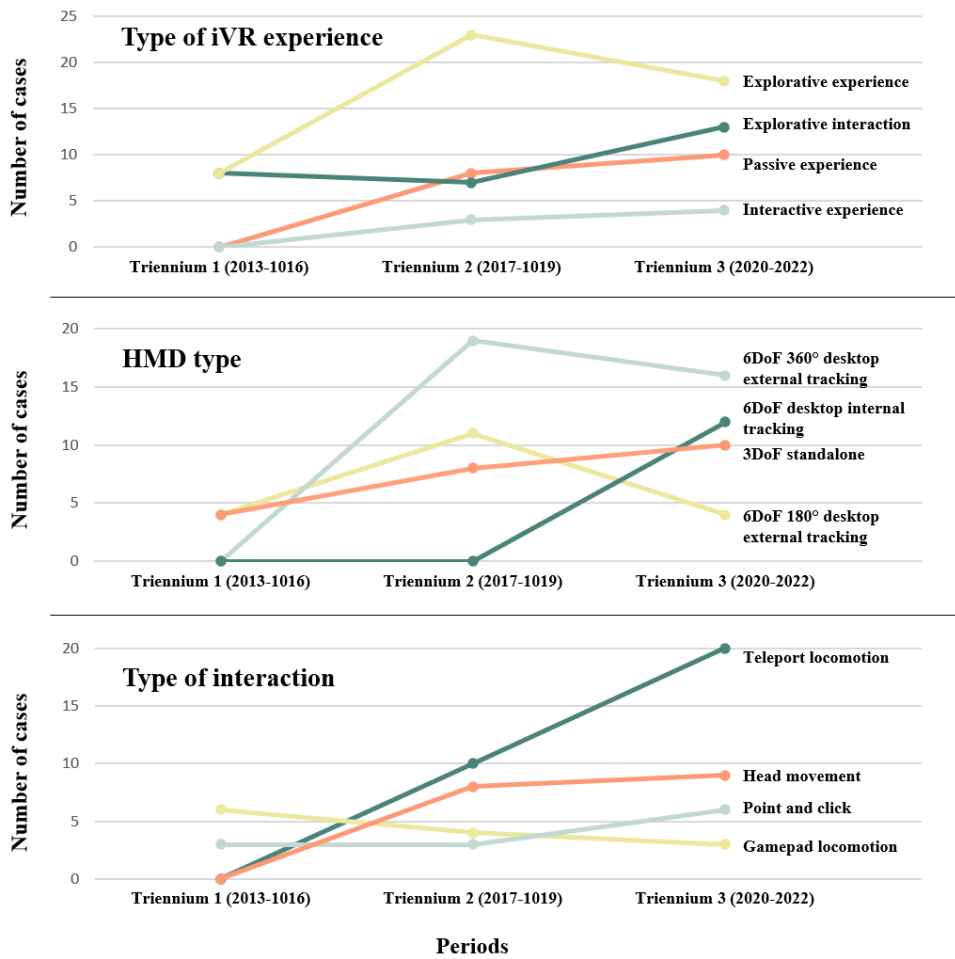


Fig. 19 Technological evolution of the type of iVR experiences, HMD type and type of interaction

The following conclusions can be drawn from the design of 3DoF experiences. The most frequently used type of movement was Head movement for Passive experiences and Point and Click for Explorative and Explorative interaction, which were the simplest of the entire taxonomy, and exclusive to those two forms of interaction in 3DoF. As depicted in *Figure 19*, Passive experiences are in a state of consolidation, showing minimal evolution in Triennium 3. Similarly, Head movement demonstrates a similar trend in a state of stabilization. Point and click shows a relatively higher increase in some cases, indicating a slightly higher

potential for evolution. Standalone 3DoF HMDs are the most widely used, although there are several cases of 6DoF 360° external trackers desktop for Passive experiences, possibly due to the eye-tracking capabilities of those HMDs. Similarly, *Figure 19* illustrates that the evolution of 3DoF standalone is mild and is aligned with the trends observed for Head movement and Passive experiences. Free was the most common type of ending, although Exploration had a majority presence in Explorative Interaction experiences, due to its greater interaction. There was no clear trend in Passive experiences, with Free, Exploration, and Time being used. Furthermore, this DoF stands out for the utilization of Recorded characters and extensive use of audio in Passive experiences. Those elements, while non-interactive, contribute life to this type of reconstructions. The findings highlight 3DoF experiences as the simplest, with the most straightforward types of interaction and the most affordable and least functional HMDs. As with other studies, the findings indicated that, if well-designed, fewer stimuli lead to greater engagement in 3DoF experiences [161, 162]. It also explains the greater use of these experiences in Musealization, as they are simpler experiences, comfortable to use in groups [20], and with lower-cost HMDs that can be marketed to individual users. The slower evolution of the number of cases related to this technology in the last triennium under analysis can in all probability be attributed to its increased technological simplicity, resulting in comparatively lower research interest.

Furthermore, the following conclusions were drawn from the design of the 6DoF experiences. Explorative experiences and Explorative interaction represent the most common type of VR experience in this DoF. Gamepad locomotion was rarely used and was mostly found in older versions, while Teleport locomotion was the most common type of movement [159]. A fact that is clear in *Figure 19*, where it is observed that as the use of Gamepad Locomotion decreases, the utilization of Teleport Locomotion doubles between triennia. Interactive experiences were an exception, in so far as Room scale became more important, due to the lack of need for movement [4]. However, Interactive experiences were less common. In terms of HMD preference, there was a shift from 6DoF 180° external tracking desktop HMDs to 6DoF 360° external tracking desktop HMDs, which are currently the most widely used, and to 6DoF internal tracking desktop and standalone HMDs. It is an understandable change, as the 360° models offer more tracking area and internal trackers give greater user comfort, due to the lack of external trackers. The same thing can be observed in *Figure 19* where it is evident that in Triennium 1, the most widely used HMD is the 6DoF 180° external tracking desktop HMD. It continues to grow in Triennium 2 but is surpassed by 6DoF 360° external tracking desktop. Finally, in Triennium 3, although there are still more instances of 6DoF 360° external tracking desktop, the trend declines, and the 6DoF desktop internal tracking HMD emerges. The most modern HMDs are primarily used with Teleport locomotion, with

6DoF 360° external tracking desktop HMDs being the preferred choice for Interactive experiences. A choice that is due to the varied range of motion sensor positions that enhance tracking. The way the ending of the experiences varied was greatly dependent on the type of iVR experience. The Free ending was the preference for Explorative experiences, while Task-related endings were preferred for Explorative interaction and Interactive experiences, due to the higher interactivity of these types of iVR experiences. Furthermore, as the complexity of the iVR experience increases, it is more common to encounter the inclusion of characters, audio, and interface. Unity was used more frequently as a development engine, but Unreal stood out, because of its ease of use in multidisciplinary teams [38] and its high Los and LoD [16]. Those characteristics make it particularly suitable for Education and Preservation applications. The greater complexity of 6DoF experiences affords greater interactivity and variability, which is beneficial for learning and research purposes. Reasons that explain the greater usage of 6DoF in Education and Preservation. The greater complexity of 6DoF implies greater interactivity and variability, which is beneficial for learning [20], but also for research, as experiences with many variables may be explored. The trend toward increased interaction can also be observed in *Figure 19*. While Explorative experiences decline in the last triennium, there is a rise in other more complex experiences such as Interactive experiences and Explorative interaction.

5.5 Evaluation

Once an iVR experience is completed, a decision on whether to assess the experience in the post-processing phase can be taken [19]. This section analyses the quantity, the purpose and the quality of the evaluations. First, the quantity of evaluations was considered, based on year of publication, then the purpose of the evaluation was analysed and, finally, the type and the characteristics of the evaluation, highlighting some examples of more complex and higher-quality evaluations.

The first analysis considered year of publication and number of evaluations. The total percentage of papers that included evaluations was 42%. In *Figure 20*, the Y axis shows all the studies divided between those that did and did not describe evaluations. On the X axis, the publication years are displayed. In the early years (up until 2017), it was relatively common to conduct evaluations or tests, but due to the small number of cases, it is not a very representative part of the sample. In the following years, it can be observed that the number of evaluations increased year by year until 2022, a year in which 50% of the papers reported evaluations.

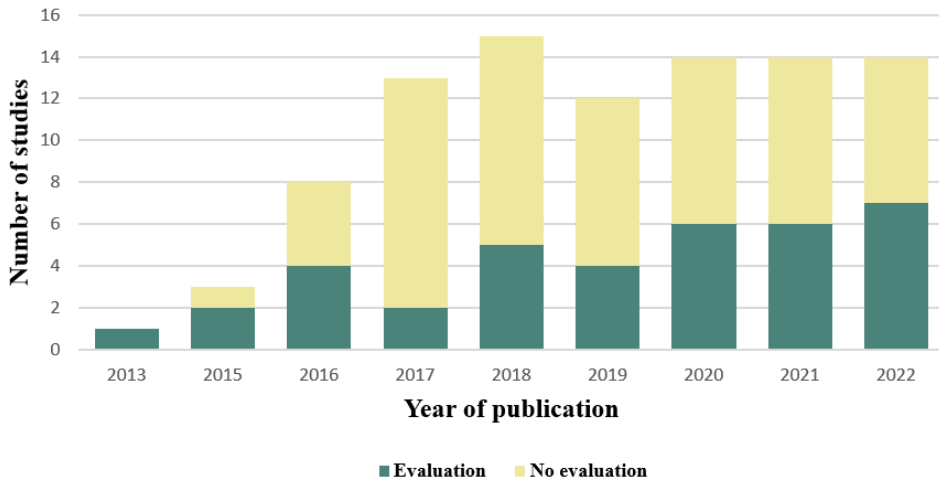


Fig. 20 Papers with and without evaluation of the iVR experience by year of publication (2013-2022)

This analysis showed that evaluations are scarce, as less than half of the reconstructions were evaluated. Despite these results, outcome evaluations are a growing trend. In recent years the percentage of cases evaluated has approached 50%, suggesting that evaluations will be increasingly common.

The following analysis will be focused on the purpose of the evaluations that were conducted, taking into account the area of application, the evaluation purpose, and the type of questions. On one hand, the most common evaluation purpose was Usability and user experience (69%), followed by Education/Engagement (20%) and Technology or System Application (11%). On the other hand, the most frequent type of question was Likert (48%), followed by Open-ended (30%) and Option (10%). The percentage usage of the evaluation purpose and type of questions are shown on the Y-axis of *Figure 21*. The areas of application are divided into two columns on the X-axis, with the data for the evaluation purpose in the left column and the type of question in the right column. In general, it can be observed that Preservation has the most extreme percentages of usage both for the evaluation purpose and for the type of question. Musealization is somewhat more balanced, while Education shows greater diversity. In Preservation, Usability and user experience were used almost exclusively as the evaluation purposes. In terms of the type of questions, it is divided between Likert and Open, with slightly more emphasis on Likert. In Musealization, Usability and user experience remain the most common purpose, but Technology or System Application and Education/Engagement are added, each with a 20% usage rate. The type of question is somewhat more balanced, with a slightly higher usage of Open questions. Finally, the most balanced area of application is Education, with

Usability and user experience having the same weight as Education/Engagement, each with a usage rate of approximately 40%. Additionally, Technology or System Application rose to 20%. Concerning the type of question, Options-based questions gain more prominence, causing Open questions to lose some of their presence.

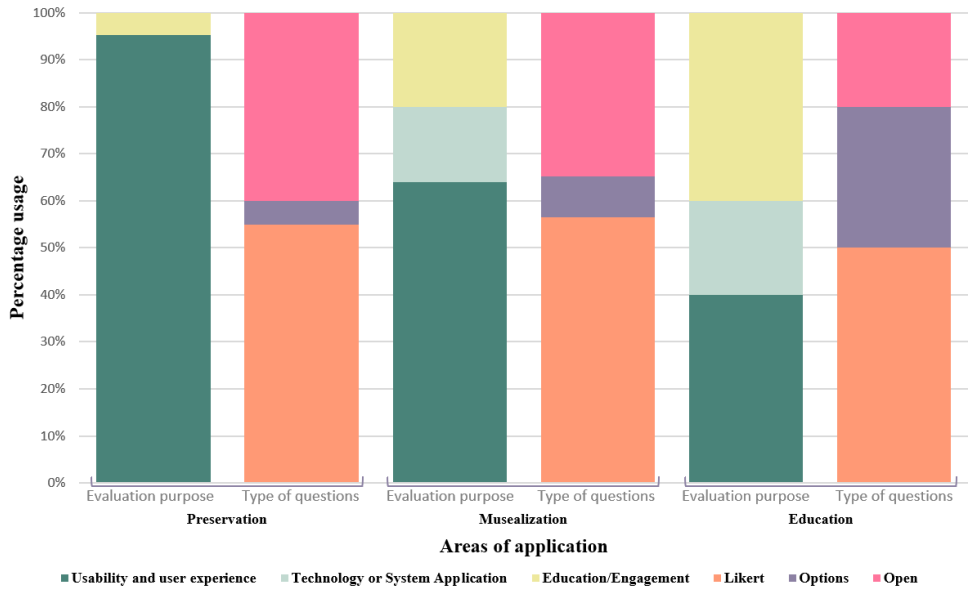


Fig. 21 Percentage usage of evaluation purpose and type of questions by area of application

From these data, the following results can be obtained. The most frequent evaluation purpose is Usability and user experience, followed by Education/Engagement and Technology or System Application. However, this distribution is not uniform and varies depending on the area of application. Preservation, not targeting a specific audience, is almost exclusively focused on Usability and user experience. On the other hand, areas of application with an orientation toward a specific audience require a greater diversity of evaluation purposes and types of questions, with Education being the primary exponent. Naturally, Education also has Education/Engagement as its main evaluation purpose, which is predictable given the nature of the area of application. These results are anticipated, as specialization in the area of application typically leads to a corresponding specialization in evaluation purpose and type of question, diverging from general trends. Additionally, these findings are aligned with the results of Checa's review of educational applications for VR [4], where the evaluation purpose is divided between Education/Engagement and Usability and user experience. Regarding the type of question, Likert is the most commonly used, followed by Open

and Options. However, as with the evaluation purpose, the usage of type of questions varies in accordance with the area of application. In this case, the only area that shows a significant difference is Education, where Options are much more used. This difference could be attributed to the fact that knowledge-oriented evaluation questions are often assessed using test-type questions, falling under the Options type of question.

The type of assessment according to the divisions between phases, the comparison of results with a control group, the sample size, and other evaluation techniques were all considered to analyse the quality of the evaluations. The indicators of evaluation quality were the number of evaluation phases, with Post being the least favourable and Pre/During/Post being the most robust. Additionally, a control group was used in the evaluation and the sample size, where a higher size was considered better [154]. Furthermore, some evaluations employed more sophisticated methods such as eye-tracking, which serves as an additional quality indicator [163]. All the advanced evaluation methods identified in the sample were not specified in the article, due to a lack of discernible patterns in their usage. The comprehensive list is available for review in *Annex II*.

Accordingly, the graph in *Figure 22* shows the percentage usage of different types of assessment and the use of control groups on the Y-axis. Each application area is represented on the X-axis. The column of each area refers to the type of assessment, and the separate areas reflect their use of control groups. The areas indicate the use of control groups across all the evaluations in each area of application. However, this percentage is not correlated with the type of evaluation in *Figure 22*. Preservation is the area with the least evaluation and where control groups are less used. Musealization ranks second with a higher presence of evaluation and the same quantity of control groups, but with simple evaluations. Finally, Education is the area where the most evaluations take place, with more complex evaluations and a greater presence of control groups.

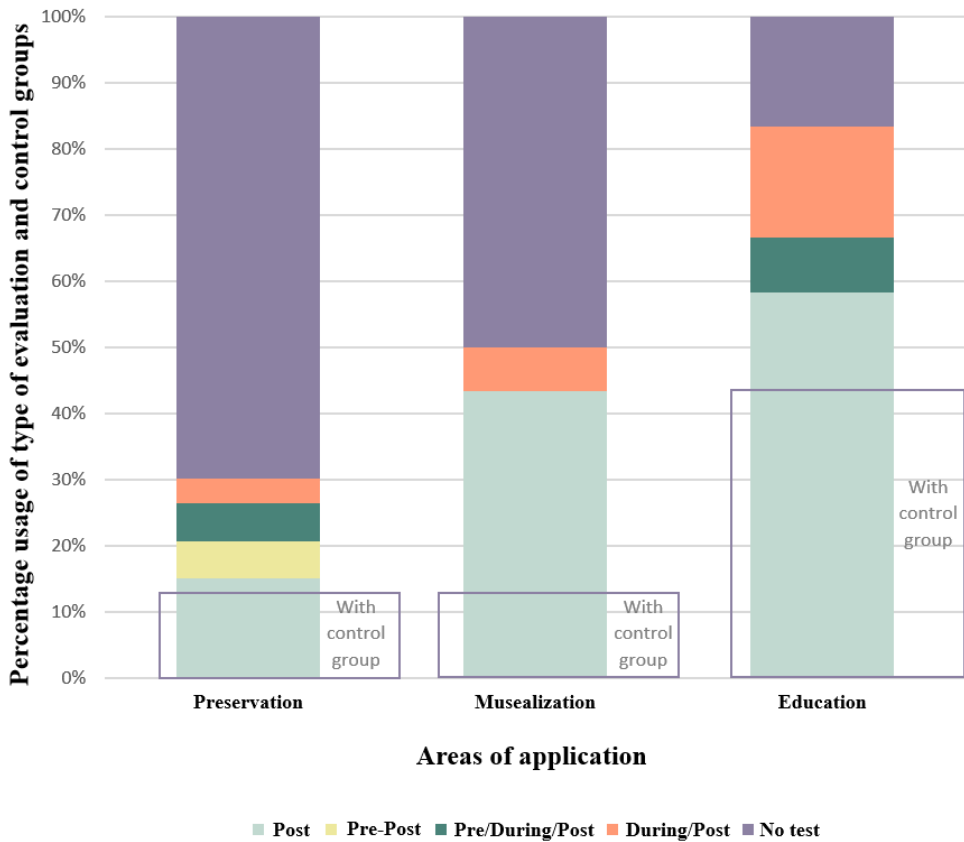


Fig. 22 Percentage usage of control groups and each type of evaluation by area of application

Regarding the sample size, the overall mean was 113 individuals, a high average which was influenced by specific evaluations with very large groups. The total median, however, was 37 individuals, indicating a more representative measure. The sample size was aligned with the same quality trend observed for the type of evaluation, with the following means (M) and medians (Md): Preservation M=50 Md=23, Musealization M=120 Md=37, and Education M=209 Md=72. Similarly, Preservation had the smallest samples, while Musealization and especially Education had the largest ones. This finding is aligned with those of other studies indicating that evaluations conducted in museums and similar environments often involve large samples [163]. Education, on the other hand, is an area that typically stands out for the robustness of its evaluations [4]. Lastly, the utilization of advanced evaluation and data analysis methods, such as eye tracking, Electroencephalogram (EEG), or Analysis of Variance (ANOVA), were considered. These techniques were employed in 9% of Preservation evaluations, 10% in Musealization, and 17% in

Education. Once again, the pattern was repeated, although the percentage was relatively low across all areas of application.

In summary, the following conclusions can be drawn. Preservation was focused on the assessment on Usability and user experience. In addition, it is the area with the highest percentage of evaluations of the lowest quality, although it has a few complex evaluations, low sample size, and few complex evaluations. The lack of evaluations within this area makes sense, given the characteristics of the experiences, which were not tested with end-users. Musealization, while continuing to focus on Usability analysis, incorporated additional purposes. This area of application was ranked second, but it had very few complex evaluations. Moreover, the size of their samples was similar to the overall mean and median, indicating that the most common practice in this topic was to evaluate with groups of around 40 people. The orientation of this area towards end-users facilitates large evaluations [163], although the difficulty of conducting complex evaluations with very large groups may explain its low quantity and quality [20]. Finally, Education can be highlighted under evaluation purposes as having a high interest in the Evaluation/Engagement purpose. This area had the highest percentage of evaluations, more complex evaluations, greater use of control groups, larger sample size and increased utilization of complex evaluation techniques. It is hardly surprising in an area where robust evaluation is one of its pillars [4]. These data coincided with other studies that indicated that the evaluation of CH experiences was poor, and with simple evaluations [154]. Nevertheless, Education showed more robust evaluations, and the number of evaluations of iVR experiences is rising in view of the valuable lessons that can be learnt from the results. Some examples of particularly robust evaluations will be provided, to conclude the findings of this subsection. The following examples stand out for their type of evaluation, sample size and use of a complex methodology. The first example involved the virtual reconstruction of Moscow's Red Square (Russia) in the 20th c. [104], utilizing a Pre/Post-evaluation method with a sample of 60 individuals, incorporating a control group, and employing Polychoric PCA as the analytical method. The second example was the virtual reconstruction of the Neolithic site of Çatalhöyük in Turkey around the 70th c. BC [101]. In this study, a Pre/During/Post-evaluation method was applied to a sample of 84 individuals, with the use of control groups and employing factor analysis and ANOVA as statistical methods. Lastly, the virtual reconstruction of La Draga settlement (Spain) around the 50th c. BC was chosen [133]. In that study, an assessment was conducted with a sample of 262 individuals, collecting data on their performance in the iVR experience, on which basis user behavior was clustered. Additionally, a post-evaluation was performed with a correlation analysis on a sample of 42 users.

6. Best design practices and future lines

In this section the most common design best practices found in the review and their application in the development of virtual reconstructions of CH in iVR will be explained. Secondly, the future lines of research of the topic will be outlined. To do so, two different types of analyses were conducted. Firstly, for the identification of best practices, a correlation analysis was performed to identify the most important variables to consider. Secondly, for the definition of future lines, a qualitative analysis supported by the results of the review was conducted.

6.1 Best design practices

A correlation analysis was conducted for the analysis of best design practices. In this sub-section, the most relevant results of that analysis will be detailed, linking the variables to the outcomes of the study. The explanation of best design practices has been organized following the same order as the *Survey section*: 1) *Data distribution*; 2) *Heritage characteristics*; 3) *Reconstruction characteristics and experience design*; 4) *Design of immersive Virtual Reality*; and 5) *Evaluation*.

Figure 23 presents the correlation matrix conducted in this study. It illustrates several variables analysed during this investigation along with their correlation coefficients represented in the matrix. Some variables were not included in the analysis, due to the noise they generated in the matrix, caused by the large amount of unspecified data, among other reasons. The correlation coefficient ranged from -1 to 1, representing absolute correlations at the extremes. The orange colours represent negative coefficients, while the green ones represent positive coefficients. The more extreme the value, the more saturated the colour. A linear progression was not always followed by the variables that were examined in this study. For instance, "*reconstruction country*" cannot be numerically compared with "*game engine*". Whenever possible, the data were coded from lower to higher, assigning lower values to variables with lower technological complexity. In the case of LoS, LoD, and LoH, values were assigned based on their scores. The complete coding of the data can be reviewed in *Annex II*. It is mentioned, due to that situation, whether the correlation was positive, negative, or indiscernible, as the data were entirely qualitative. Considering the abundance of correlations in the text, only those values below -0.30 or above 0.30 will be discussed. Similarly, in *Annex II*, the complete analysis can be reviewed, including its p-value. It is essential to note that the correlation between values implies no causality and that these data will be discussed considering previous results.

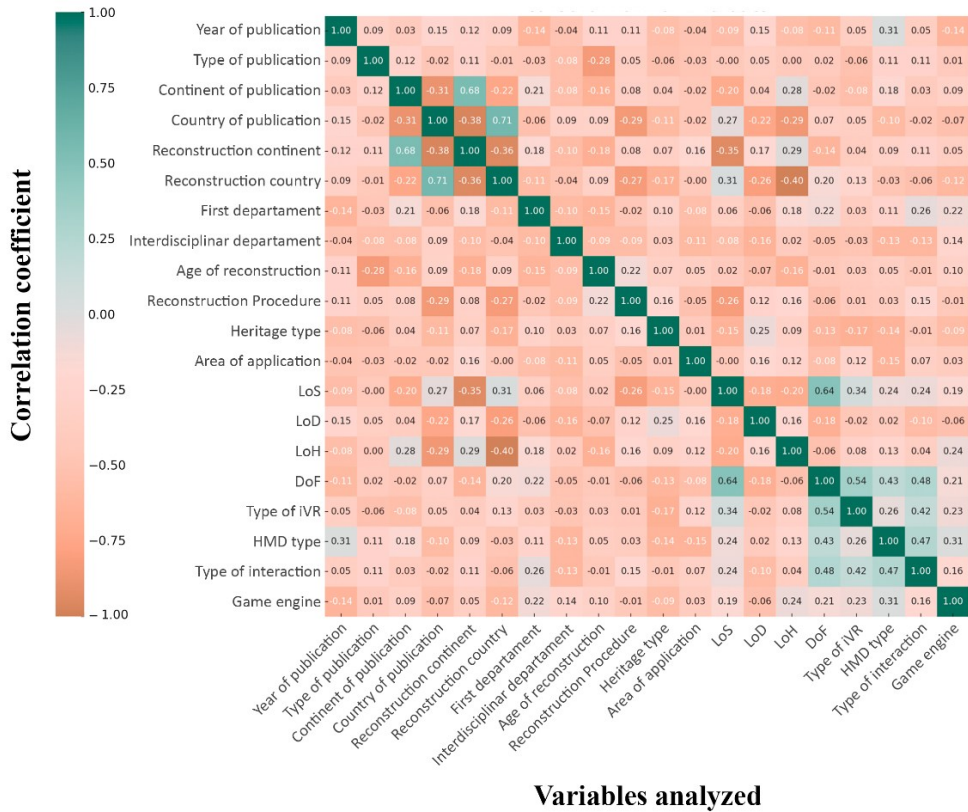


Fig. 23 Correlation matrix of the most relevant variables

Firstly, continent of publication has a correlation of -0.68 with reconstruction continent and -0.31 with country of publication. Similarly, country of publication has a correlation of -0.38 with reconstruction continent and 0.71 with reconstruction country, and reconstruction country has a correlation of -0.36 with reconstruction continent. In this case, no distinction could be drawn between positive and negative correlations, due to the qualitative nature of the data. The high correlation coefficients in these variables indicate something that could already be observed in the previous analysis: there is a strong relationship between the place where the reconstruction is developed and the location where it is situated. Whilst it may be true that Europe and Asia, for example, hosted more reconstructions than they produced, that percentage was not excessively high.

Assessing the heritage characteristics, it can be observed that they also yielded noteworthy correlation coefficients related to geographic variables. On one hand, LoS has a correlation of -0.35 with reconstruction continent and 0.31 with reconstruction country. On the other hand, LoH has a correlation of -0.40 with

reconstruction country. Similar to the previous correlations, no distinction can be drawn between positive or negative signs, due to the qualitative nature of the data. The following conclusion can be drawn in relation to those correlations and the previous results. As discussed in this study, there are reconstructions that stand out because of their low LoS but high LoH, usually related to RPs based on reForm. Many of those reconstructions are of Roman heritage, located in Italy and Spain, so the correlation could be attributed to that reason.

Finally, the variables related to iVR design stood out because of their high correlation coefficients. The values presented below were linearly encoded, so that either positive or negative correlations could be considered. Firstly, DoF has shown positive correlations with LoS (0.64), type of iVR (0.54), HMD type (0.43), and type of interaction (0.48). Those correlations are aligned with the results of the article. On one hand, the lowest DoF (3DoF) has the lowest LoS, many of them being 360° environments, more limited types of iVR experiences like Passive, HMDs with fewer degrees of freedom, and simpler types of interaction, such as Head movement. On the other hand, the highest DoF (6DoF) has higher LoS, with freedom of movement, more complex types of iVR experiences such as Explorative interaction, modern HMDs, and types of interaction with more freedom of movement, such as Teleport locomotion. Additionally, type of iVR has a positive correlation with type of interaction (0.42). This also corresponds to the study's results, with more complex types of iVR typically having more freedom in types of interaction, such as Teleport locomotion. Lastly, it is observed that HMD type has positive correlations with year of publication (0.31), type of interaction (0.47), and game engine (0.31). Aligned with one of the conclusions of technological evolution, it indicates that as the years passed, HMDs evolved to have more functionalities. Thus, advanced HMDs with more functionalities tended to use Teleport locomotion as a type of interaction. Similarly, more complex HMDs, such as 6DoF 360° desktop external tracking, require powerful game engines such as Unity and Unreal Engine.

6.2 Future Lines

Considering the reviewed papers and the results extracted from their analysis, the following future lines of the discipline have been extracted:

- Advances towards increasingly better and affordable scanning and photogrammetry techniques will make reconstructions based on digitalization techniques more common.
- 3DoF experiences have clear preferences, few variables and have therefore reached high levels of maturity. This trend is expected to continue, resulting in fewer cases in research and a focus on experiences that are entirely geared towards end-users. Further specialization is likely in Musealization where

- 3DOF characteristics are especially suitable for large groups. Regarding 3DoF, the only current trend that may change is the use of Point and click, which will increase usage in favour of slightly more interactive experiences.
- 6DoF experiences will become more common, due to their potential in university research. It will perhaps mean that Explorative interaction will become more relevant within this DoF. The increase in interactivity will lead to more Task-based conclusions and the complete disappearance of Gamepad locomotion. Furthermore, the usage of characters, sound, or interface is expected to increase, as they are more necessary in more complex experiences. It is possible that this trend will evolve towards a more complex use of sensory feedback, such as biofeedback. With regards to HMD usage, the 6DoF 360° external tracking desktop HMDs will be replaced by the 6DoF internal tracking desktop and standalone HMDs.
 - 6DoF experiences will become more important in the future, as 6DoF HMDs become more functional and affordable.
 - The number of Education experiences will increase, as they have the greatest potential for university research, due to their interactivity and the availability of better evaluations.
 - The use of simple game engines will increase in this field, meeting the needs of multidisciplinary teams with less knowledge in computer science.
 - Evaluations will increase in quantity and quality. 3DoF will evaluate more aspects of usability, design, and device selection with end-users. In contrast, 6DoF will focus on educational aspects or the usability of iVR itself to make this technology more accessible to end-users.

A two-colour scale, grey and orange, is proposed for the qualitative assessment that concludes this section. *Figure 24* presents a summary of the most common and promising solutions, divided between 3DoF and 6DoF experiences. Each DoF is divided into five sectors, which were the most important categories analysed in each section of the review: 1) reconstruction procedure; 2) area of application; 3) type of IVR experience; 4) Head Mounted Display; and 5) type of interaction. The size of the circles represents the current number of cases. The orange circles denote the solutions with the greatest growth potential in each sector. The solutions marked with higher growth potential in orange have been outlined by experts involved in the development of virtual reconstructions of CH in immersive iVR based on the results of the analyses presented in the article. This assessment system has been used in other reviews related to technological solutions and CH, such as the reviews by Lucchi in CH and photovoltaic systems [164, 165].

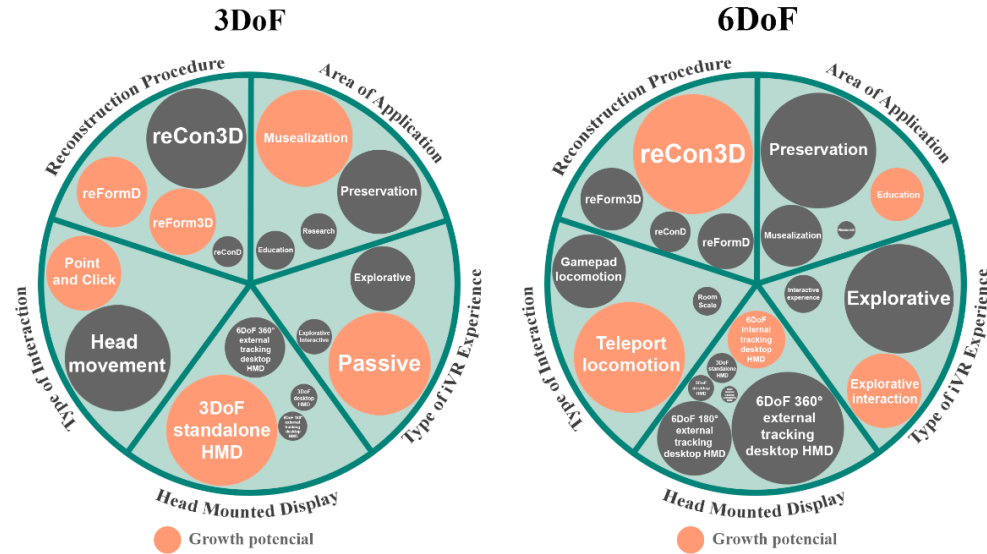


Fig. 24 Summary of the most common and promising characteristics in 3DoF and 6DoF experiences

7. Conclusions

The use of iVR in the virtual reconstruction of CH is an expanding tool with educative potential that deserves further attention. This technology has significant room for improvement that needs further research, particularly into 6DoF experiences. Based on the analysis of this sample, the following paragraphs respond to the questions posed in Figure 1, including *Methodology* and *Data distribution* section. Some questions have been grouped to facilitate their response. In each paragraph, the title of the question is highlighted in bold, followed by the response.

To answer “Conclusions on methodology. Not asked in Figure 1”. Standardizing the taxonomy for iVR and virtual reconstruction of heritage is crucial. During the search for papers, many were found that could not be fitted into the chosen taxonomy. There were numerous papers that described virtual reconstruction such as photogrammetry or iVR for computer game experiences. As a proposed solution, the taxonomy outlined in the *Methodology* and *Taxonomy* section should be adopted.

To answer “Conclusions on data distribution. Not asked in Figure 1”. The discipline is in a state of consolidation, having reached its peak production in 2018. These articles are distributed between conference papers and journal articles, with an increasing trend toward publication in journals. Geographically, Europe stands out as the continent with the highest production and the most reconstructions located,

with Italy and Spain being prominent within the continent. On the other hand, Asia occupies second position both in terms of production and localization. Lastly, the discipline is clearly interdisciplinary, combining technical and historical disciplines, with a pronounced emphasis on technical aspects.

To answer “Do nationality, period, preservation, and type of heritage influence the reconstruction and its future use? Are there more viable characteristics for a reconstruction?” Nationality, period, RP, and heritage type have a notable influence on the subsequent development of an iVR experience. The most common and constant cases are those of reconstructions of urban cores and sacred heritage, with processes based on reConstruction rather than reForm. However, the production peaks consist of papers on Roman history and Contemporary-Age, Civil and Industrial heritage. Peaks that are probably due to the use of digitization in these reconstructions, which makes the process more affordable and gives it greater historical accuracy. Additionally, reconstructions are typically located in the same country where they were developed.

To answer “What are the characteristics of a reconstruction in iVR? Do the characteristics of the reconstruction influence the design of the experience and its area of application?” During the analysis, it has been observed that LoS, LoD, and LoH are highly effective values for assessing the features of a virtual reconstruction. The RP of the reconstruction influences their characteristics. The use of reForm was associated with a low LoS and many instances of 360° environments, but those experiences stand out because of their LoH. On the one hand, cases of reConstruction have a very high LoS but a lower LoH. Those characteristics are relevant when creating the iVR experience. A low LoS combined with a high LoH are recommended features for 3DoF Musealization experiences, as a simpler, more compact experience is more usable for large groups. Also, a high LoH provides historical accuracy. On the other hand, LoS proves to be relevant for 6DoF Education as it facilitates the inclusion of interactive elements and the exploration of large environments.

To answer “What are the most popular areas of application and types of iVR? What characteristics should reconstructions have in each area of application? What is the most recommendable type of iVR for each area of application?” Preservation is the most common area of application, although its characteristics hardly stand out, due to its lack of a specific target audience in the context of this study. These characteristics are relatively low as they are not intended for end-users. It is an area where primarily Explorative and 6DoF iVR experiences are developed, which are the most common type of iVR experience and the most prevalent DoF. Musealization is the second area with the highest number of cases. It stands out for featuring reForm reconstructions with a low LoS and a high LoH, along with a significant number of

360° environments. Explorative iVR experiences are predominantly developed in this area, as they are the most common type of iVR experience. However, there is also a notable concentration of Passive experiences within the same area. Similarly, 6DoF experiences are the most popular, though nearly half of all 3DoF experiences are found within the area. Lastly, Education is the least frequent of the three areas. It features reconstruction with a very high LoS. As a result, most experiences within this area are Explorative Interaction, with 6DoF being more prominent than 3DoF.

To answer” What is the most suitable design for each type of iVR experience? What are the most widely used HMDs and game engines for each type of iVR experience?” 3DoF experiences usually have the following design characteristics. They are iVR experiences with a strong emphasis on Passive experiences, primarily controlled through Head movement. Point and click interaction is also used in experiences with more interactivity, such as Explorative ones. These experiences often have either with Free or Exploration endings, after the entire content has been viewed. These experiences can be complemented with the use of Recorded characters and audio. The most widely used HMD is the 3DoF standalone. The affordability of the procedure and HMDs, along with the simplicity of these experiences, make them highly recommended for groups. Additionally, thanks to RPs based on digitalization, these experiences tend to have a high LoH, making them particularly suitable for Musealization. There is therefore widespread overall consensus on the path to be followed for the development of this type of experience. 6DoF experiences usually have the following design characteristics: Explorative and Explorative interaction experiences. They are predominantly controlled through Teleport locomotion, the most common type of interaction. However, in Interactive experiences, Room scale is the most frequently used, as it requires less movement. The endings of these experiences are usually Free, although in cases with more interaction, the endings tend to be Task-related. Currently, the most widely used are 6DoF 360° external tracking Desktop HMDs. However, it is expected that in the future, there will be a shift towards 6DoF internal tracking desktop and standalone HMDs. As these experiences gain complexity and interaction, it is more common to find elements such as characters, audio, and interface. Their higher level of interaction means that these experiences are more suitable for Education and Preservation experiences conducted in university settings. However, the increased complexity and higher development costs make them less accessible to users, both individually and in groups. Nonetheless, their versatility and potential make them particularly noteworthy in the fields of Education and Preservation. Unlike 3DoF experiences, there is less consensus regarding the use of tools in 6DoF experiences, indicating ongoing developments and research prospects.

Simple game engines play an important role in this discipline, particularly for teams with limited programming expertise. Moreover, these sorts of game engines can achieve high levels of LoS and LoD. Game engines are more important in 6DoF experiences, as it is not always necessary to use those engines for the development of 3DoF experiences.

To answer “How has technology evolved in this field?” On one hand, 3DoF experiences have shown little evolution. They gain importance in the second triennium, but the associated technologies barely gain significance in the last triennium, where Point and click is the only one showing an upward trend as a type of interaction. On the other hand, 6DoF experiences demonstrated significant evolution. Despite Explorative being the most common type of iVR experience, a clear trend has been observed in the last analysed triennium, with a decline in its importance in favour of Interactive experiences and, especially, Explorative interaction. The use of HMDs has also undergone significant transformations, with 6DoF 180° desktop external tracking being the most used in the first triennium, 6DoF 360° desktop external tracking dominating in the second triennium, and although still prominent in the third triennium, it is almost equalled by 6DoF desktop internal tracking, which is likely to become the most common HMD in the coming years. Regarding the type of interaction, there has been a shift, with Gamepad locomotion being the most common in the first triennium but being significantly surpassed by Teleport locomotion from the second triennium onwards. Overall, even in 3DoF experiences, the technological evolution in this field is progressing towards more interactive experiences with user-friendly technologies.

To answer “How much is evaluated in this topic? What areas of application have more and better quality evaluations?” Improved evaluation techniques are necessary to advance the discipline. Currently, only less than half of papers include an evaluation, a minority of which with a control group. Preservation was the area of application with the fewest evaluations and the highest percentage of low-quality assessments. It also had the lowest sample size and fewer complex evaluations. The predominant evaluation purpose in this domain was almost exclusively Usability and User Experience. These results could be attributed to the fact that Preservation lacks a defined target audience. On the other hand, Musealization was ranked second in the number of evaluations, but its quality was only slightly better than Preservation. It showed limited use of control groups and complex evaluations. However, its sample sizes were larger, averaging around 40 participants per study, and its evaluation purposes were more diverse, including Education/Engagement and Technology or System Application. The variability in purposes and larger sample size may be due to the context of these studies, involving iVR experiences for larger groups, which, in turn, complicates the execution of more complex

evaluations. Finally, Education is the area of application with the highest number of evaluations, greater quality, larger sample size, and more diversity in evaluation purposes, prominently featuring Education/Engagement. It reflects the common observation that Education stands out as an area with highly robust assessments.

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Data availability. The following supporting documentation can be downloaded at: https://universidaddeburgos-my.sharepoint.com/:f/g/personal/brunorg_ubu_es/EmJze3yarcxOhZoaek8KKCMbPgX2dGbsr7qGD7pI0iyLg?e=lcEizz “Annex I: PRISMA statement”, “Annex II: Spreadsheet used in data analysis”, “Annex III: Level of Detail system” and “Figures” (including all article’s figures).

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This publication delves deeper into the future lines proposed in *Result 1* addressing the management and optimization of LoD as one of the crucial elements in the development of 3D models for CH reconstructions, allowing a high immersion and presence in iVR. To this end, the study presents a user-friendly add-on for the open-source 3D modeling software Blender for classifying 3D models according to their LoD. The add-on was evaluated through a subjective assessment comparing the scores given by the software with those of groups of 3D modeling professionals and students. This software is specifically designed for users with limited technical expertise in 3D modelling or iVR development.

The outcomes of this publication complement the taxonomy proposed in *Result 1* with a system that enables a systematic and consistent analysis of LoD by non-expert users, thereby supporting more effective optimization of this factor. The evaluation yielded very satisfactory results with correlations values around 0.8. This result is aligned with Goal 2. *Table 4* presents the bibliometric data of this publication.

Table 4. *Bibliometric data of Result 2*

TITLE	LoDCalculator: A level of detail classification software for 3D models in the Blender environment
STATE OF PUBLICATION	Published
JOURNAL	SoftwareX
DATE	2025
JCR	Q2 Computer Science, Software Engineering (2023 release)
DOI	<i>10.1016/j.softx.2025.102107</i>
AUTHORS	Bruno Rodriguez-Garcia, Ines Miguel-Alonso, Henar Guillen-Sanz, Andres Bustillo
KEYWORDS	3D modelling, Level of detail, Virtual reality, Model classification

LODCALCULATOR: A LEVEL OF DETAIL CLASSIFICATION SOFTWARE FOR 3D MODELS IN THE BLENDER ENVIRONMENT

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Abstract. The use of Level of Detail (LoD), a crucial technique in the development of 3D models, implies lower cost graphics and resource economies. These savings are evident in contexts where technical resources are limited, such as immersive Virtual Reality and whenever LoD is critical for accurate representation, such as Cultural Heritage dissemination. Consequently, various systems are used to classify 3D models based on their LoD. However, those systems have several shortcomings that hinder their widespread use. In this research, LoDCalculator, an add-on for Blender open-source modelling software, is presented to address such shortcomings. LoDCalculator ensures unambiguous, universal, and accessible classification of 3D models. It was tested by classifying 12 3D models. The scores were then compared with the evaluations of a group of students and professional 3D modelers in a subjective evaluation. The results of the comparison were satisfactory, showing minimal significant differences between the software and the evaluation group classifications.

Code metadata		
Nr	Code metadata description	Metadata
C1	Current code version	1.0
C2	Permanent link to code/repository used for this code version	https://github.com/DigiUBU/LoDCalculator
C3	Permanent link to reproducible capsule	N/A
C4	Legal Code License	Mit License.
C5	Code versioning system used	Git
C6	Software code languages, tools, and services used	Blender, python
C7	Compilation requirements, operating environments & dependencies	Blender≥ 2.83 LTS
C8	If available Link to developer documentation/manual	https://xrailab.es/cases/lod-calculator/
C9	Support email for questions	labxrai@gmail.com

1. Motivation and significance

The Level of Detail (LoD) concept dates back to 1976 [1], although technological adaptations have over time enabled new advances. It is a feature of great importance in 3D modelling, defining the degree of similarity between an object and its virtual representation [2], and affecting the development and application of 3D models [3]. It is likewise a key factor in 3D modelling projects, as a higher LoD requires more computational and economic resources [4]. The use of LoD is varied on the basis of distance to the user, balancing visual fidelity and performance, so that it is not

excessively used [5]. Additionally, determining the LoD of a 3D project considers factors such as the display device and hardware [6].

Proper management of LoD is even more critical in immersive Virtual Reality (iVR) developments for all the above reasons. Projects of that sort where the user is free to inspect 3D models closely will typically require a higher LoD, as noted by several authors [7,8]. This challenge adds to the computational cost of rendering for each eye [9] and the higher LoD required for interactive models [4]. Furthermore, many iVR devices are standalone, meaning the entire rendering process occurs within the iVR device, which has lower power compared to a conventional computer [10]. iVR is a rising technology [11] excelling in multidisciplinary applications such as education, training, and Cultural Heritage (CH) dissemination [12]. In the field of CH dissemination, proper LoD management is also crucial. Such projects typically require maintaining the original structures of objects [13], and avoiding oversimplifications to preserve historical accuracy [14].

Consequently, several popular systems currently classify 3D models based on LoD, such as CityGML and BLOM [4]. Nevertheless, those systems have certain limitations that hinder their widespread use. Even though CityGML is the most standardized, there is no total consensus [15]. Some of the most significant limitations are: 1) the ambiguity of classification systems for semantic thresholds, as highlighted in several studies [[16], [17], [18], [19], [20], [21]]. Furthermore, most systems use discrete LoDs, with a series of defined levels [22]. When combined with semantic LoDs, limitations arise when a model cannot be fitted into any of the proposed levels, creating outliers [23]. 2) Lack of universality; those systems are designed for specific contexts, such as CityGML and BLOM, which specialize in urban environments [24]. Their specialization restricts their use in other contexts and complicates comparative analyses. 3) They are not accessible to all audiences, as some require multiple steps and extensive knowledge of 3D modelling [25]. Although the complexity of 3D models has been analysed in other research, those studies have been focused on the differences between versions of a 3D model [[26], [27], [28], [29], [30], [31], [32]], in this regard, Grande's research [33] presents a wide range of techniques and tools for measuring LoD and explores their applications in iVR projects. Moreover, the distribution, installation, and use of those software solutions is quite specialized, making them less accessible to less specialised teams.

1.1. Contribution

This research presents LoDCalculator, a software tool for classifying the LoD of a 3D model, which addresses the previously discussed issues. LoDCalculator is an add-on that works with the open-source 3D modelling software Blender and has been designed to tackle the challenges of threshold definition, universality, and

accessibility. LoDCalculator has been tested in CH environment models intended for iVR visualization, for the reasons indicated in the introduction, but it can be used as a general 3D model classification tool, especially in multidisciplinary teams because of its ease of use. Additionally, its open-source nature allows for threshold modifications to improve the classification of other specific types of 3D models.

2. Software description

In this section, an explanation is given of the software design that was developed to overcome the previously mentioned limitations, followed by the operational details of the software.

2.1 Software functionalities

In *Table 1* the decisions guiding the design of the LoDCalculator are detailed. Each decision will be explained in more detail in the text, following the same order as in the table, before a full explanation of the software is given. Certain aspects briefly presented in this section, such as the nature of the data, its extraction, and processing, will be further elaborated in *Section 2.2* and are showcased in *Fig. 2*. An important point to clarify that also influenced the design decisions is that the LoDCalculator is a general-use software. It is particularly suited to the analysis of CH models, although it can analyse any type of 3D model that projects realistic visualizations.

Table 1. Summary of the design decisions taken to develop the LoDCalculator

Issue	Threshold ambiguity		Universality of the system			Accessibility of the system	
	How to define thresholds	What type of data to use	Measurement type	Geometric data type	Radiometric data type	Distribution	Usability
Solution	9 discrete thresholds with formal boundaries	Continuous formal data extracted from the 3D model	Relative measures based on geometric and radiometric features	Quad-based geometric model analysis (mean angle, PC and vertex concentration)	Texture based material analysis (relative resolution and complexity of materials)	Open-source add-on for open-source software	User-friendly in the Blender interface, only one button and error notification

Formal thresholds were used to define unambiguous thresholds. However, those thresholds, based on the technical specifications of a model, can also create outliers [34], due to variations in specific features and modelling techniques. A system of formal thresholds based on continuous data from the 3D models was implemented to address that issue. Clear boundaries between each threshold were established, the limits of which were defined on the basis of all the data. So, the first design decision circumvented interpretation errors and results in a total of nine possible scores, ranging from 1 to 5 at half-point intervals. That number of possible LoDs was aligned with existing standards, such as the 10 levels in the GoG [9], the four levels in

BLOM3D [4], the five levels in CityGML [19], and the five levels defined by The American Institute of Architects [4].

To address the issue of universality, it is necessary to use relative measures rather than absolute ones, in the same way as the most popular 3D model simplification algorithms do, such as Edge Collapse, Vertex Removal, or Cell Collapse [5]. Although Polygon Count (PC) can indicate the LoD [35], that parameter is not applicable in all cases. For instance, the number of polygons for a single object in a 3D model will in all likelihood be fewer than for an entire city, regardless of the LoD. Moreover, 3D models composed of multiple meshes are expected to lack uniform LoD across all components [36]. So, the following parameters were considered in the analysis. Firstly, geometric fidelity, which refers to the fidelity and surface detail of the 3D model. Secondly, radiometric fidelity, which pertains to accurate reproduction of its visual properties. Both parameters are based on the Münster classification of 3D models for digital reconstruction in the context of humanities research [37]. Lightning parameters were not considered, as that factor was external to the 3D model and varied depending on the game engine. The data used to analyse geometric and radiometric fidelity, respectively, are explained in the following paragraphs.

The software was designed to analyse polygon-based models to ensure the comparison of geometric data, bearing in mind that any parametric model can be converted into a polygon-based one, but not vice-versa. Although those models are usually composed of triangles or squares, the software is specialized in square-based models that are the most common modelling shape [38]. Additionally, more topological differences can be observed in quad-based model tests, making those sorts of models easier to analyse. The decision excludes photogrammetric models, except for those that have been re-topologized, as the mesh of those models is usually generated from triangles [39]. Nonetheless, photogrammetric models are generally characterized by high realism [40].

Considering radiometric properties, a distinction can be drawn between procedural materials and texture-based materials [41]. Texture-based materials utilize images projected onto the 3D model to define its visual properties, whereas procedural materials blend procedural patterns to generate the visual appearance of the 3D model [42]. The software has been designed to analyse texture-based materials, as procedural materials can be converted into textures [43], but not vice-versa. Moreover, this workflow is the most common one when working with game engines [40], particularly in CH projects [43].

On one hand, the accessibility problem is linked to economic factors, as some of the systems of that sort require payment and are based on proprietary 3D-modelling software [2]. As an estimate, some of the most popular 3D modelling software, such

as Cinema 4D, 3D Studio Max, or Maya [44], fall within a price range of €700 to €2000 per annual license, with the latter being the most common price. On the other hand, the systems are often complex to use, especially for individuals who are not fully proficient in 3D modelling, which is common in CH work [45,46], as well as in other multidisciplinary environments related to iVR. The software has been developed as an open-source add-on for Blender, one of the most popular open-source 3D modelling software [2], to address that issue. Usability is enhanced by directly integrating data into the Blender interface with a single interactive button. After installation, a module is added to the scene properties, displaying information on the 3D model, which includes both raw data and the LoD assessment. If any errors are detected, specific notifications appear on an interface panel, guiding the user to rectify the analysis. That feature ensures that novice users can avoid mistakes. *Fig. 1* illustrates the interface panel on the right side of the screen showing the results of the Utah Teapot analysis.

Furthermore, its open-source nature permits modifications, enabling adjustments to both the LoD thresholds and the software functionality. This flexibility facilitates analyses of more specific models than those detailed in this research.

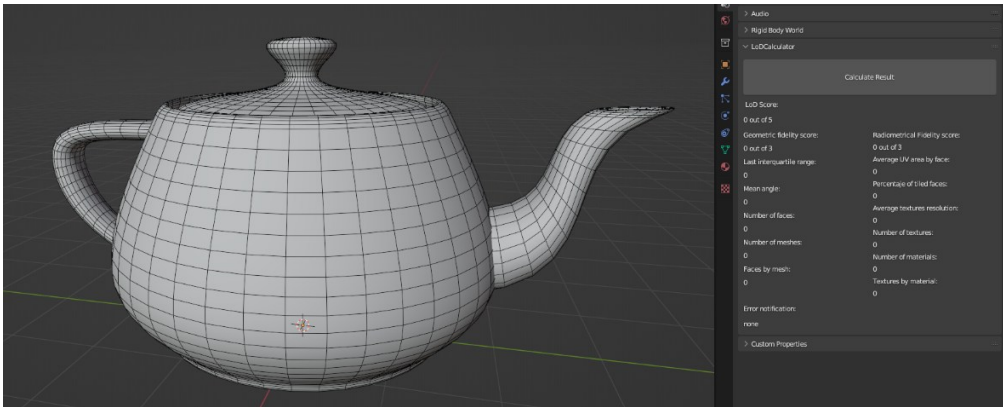


Fig. 1 Interface of LoDCalculator in the right panel. It shows the activation button and the results of the Utah Teapot analysis

2.2 Software architecture

The LoDCalculator was developed in Python using the Blender Python API. The process of acquiring and processing data for geometric and radiometric fidelity is outlined in this section, as well as the procedure for assigning LoD scores. *Fig. 2* provides an overview of the software process. Vertically, it depicts the steps from accessing the 3D model data to assigning a score, illustrating how each step impacts the data flow, the process can be divided into the following phases separated in *Fig. 2* with the grey dashed rectangles:

1. *Acquisition and Processing of Geometry Data*: This phase focuses on gathering and processing geometry data to calculate geometric fidelity.
2. *Acquisition and Processing of UV Data and Materials*: This phase is divided into two sub-steps:
 - 2.1 *UV Mapping Data*: Obtaining and processing data associated with the UV mapping of the 3D model.
 - 2.2 *Materials Data*: Obtaining and processing data related to the model's materials.
3. *Assignment of Scores*: once acquired, the data are processed to obtain the final LoD score.

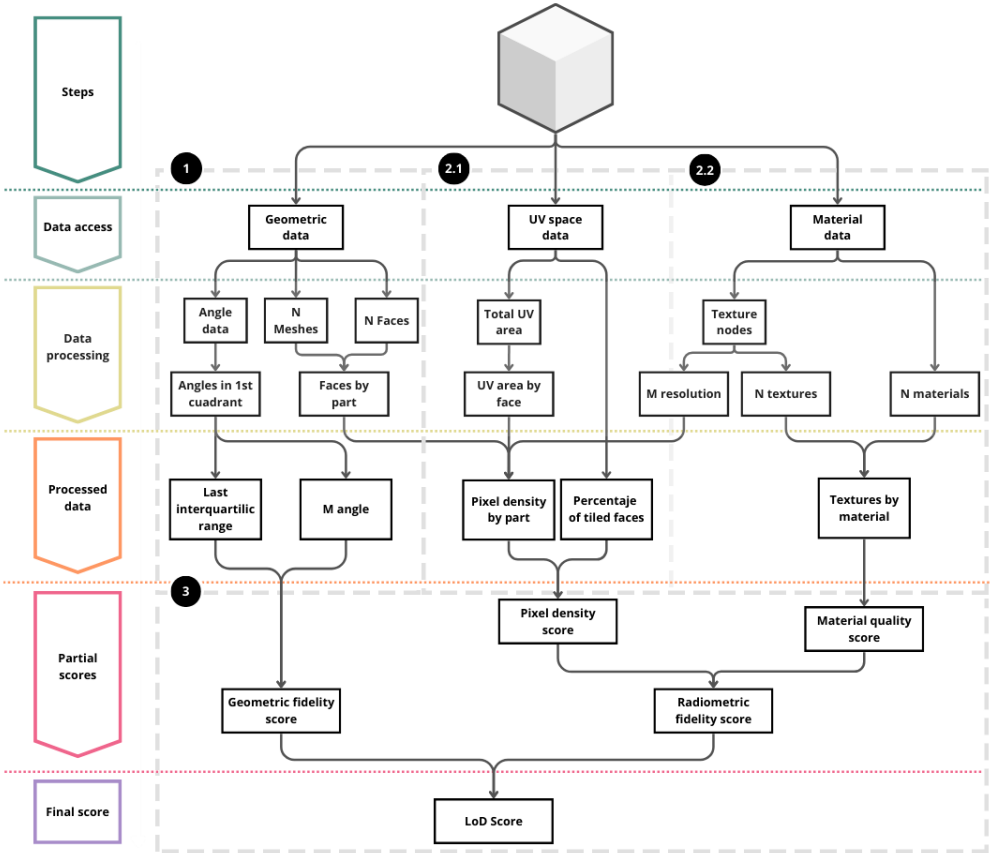


Fig. 2 Summary of the procedure of LoD Calculator. Vertically it shows the steps from the access to the 3D model to the assignment of the score. The gray dashed rectangles separate the main phases of the process

The data used to evaluate geometric fidelity include face angles and the number of faces per mesh in the model. Following a similar approach to Zhao [47], vertices with smaller angles were considered to contribute more information. Low-poly 3D models show higher angle values along their edges, as the large angles provide

crucial information. Consequently, a lower number of consecutive steps along a slope indicates a less smooth surface, signifying a lower LoD [38]. When working with relative data, the PC is divided by the number of meshes in the 3D model, yielding the average polygon resolution per mesh. By doing so, comparability between models, whether a few parts of a single mesh or a larger model, is facilitated. The face angles are extracted and normalized to the first quadrant to enable comparison of angles in any direction. Those angles are then divided into quartiles. A higher concentration of smaller angles indicates a more detailed model, as it includes finer details and depicts smoother slopes. This approach allows for the evaluation of geometric surface distortion and detail, similar to previous studies on point cloud surfaces [48]. The degree distance of the last interquartile range is used as a metric: a greater distance from the last interquartile range implies a lower concentration of angles close to 90° , indicating finer details. The average angle within the 3D model was then computed, with higher averages indicating less detail. Lastly, the average number of polygons per mesh was calculated to arrive at the PC.

The mean texture resolution and the proportion of textures per material were chosen as indicators, to evaluate radiometric fidelity, as noted by several authors [39,40]. To do this, the average area occupied by the polygons of the 3D model in the UV space was computed for a relative calculation of texture resolution. The area of each polygon was calculated using a bounding volume circle for area, the simplest and most adaptable procedure, in order to generalize the process [49]. Later, the material nodes were accessed to count the number of materials and texture nodes, and the associated textures were accessed to calculate their mean resolution on one axis. This average area of the UVs was multiplied by the mean texture resolution and the average number of faces per part of the 3D model. In doing so, the mean resolution needed to texture each mesh of the 3D model without overlap could be determined. Additionally, the percentage of polygons with an unwrapped surface area exceeding 100 % of the UV space was calculated, assuming that the textures applied to those polygons were tiled and repeated across their surface area [50].

The data were divided using three thresholds to calculate the LoD score. The data collected in the previous phases were approximated or general, due to generalization; thus, only three thresholds were used to promote coherent segmentation and to avoid outliers. This is one of the system's limitations, as a higher number of thresholds could lead to outliers. However, the selected number aligns with classifications approaches commonly used for LoD in video games and interactive environments [51]. The mean angle value and the range of the last quartile were segmented to obtain three possible scores for geometric fidelity. Radiometric fidelity was calculated by averaging two sub-scores, each with three levels: one based on the proportion of textures per material, and the other on the

mean resolution per mesh and the percentage of tiled faces. Finally, both scores were summed and 1 was then subtracted from the result to compute the LoD score. The result was a score ranging between 1-to-5 at half-point intervals on a scale that was similar to other popular scoring scales, such as the Likert scale, making it familiar to a wide range of users. The entire LoDCalculator workflow, including the value ranges used for the thresholds, can be accessed in the LoDCalculator .py code available in the repository.

3. Illustrative examples

LoDCalculator was tested by evaluating 12 models of CH environments, although it can be used in other contexts as well. The results were then compared with evaluations from two groups: the first group consisted of 41 students from 3D modelling courses at the University of Burgos of the bachelor in Video Game Design, and the second group comprised 24 professionals in 3D modelling and animation. Of the 24 professionals, 11 were juniors, meaning they had less than 3 years of professional experience. On the other hand, 13 were seniors, with expertise exceeding 3 years. Those groups operated similarly to the software, assigning scores of 1-to-3 for geometric fidelity, 1-to-3 with half-point intervals for radiometric fidelity, and the LoD score of 1-to-5 with half-point intervals. Before starting the evaluation, some examples were shown to familiarize the users and to obtain more accurate results [52]. For each 3D model, users viewed six renders: 3 clay and 3 with textures with similar lighting. All renders were only illuminated with ambient light generated by a cubemap and rendered using Blender's real-time Eevee engine with default settings to produce comparable images. This subjective method of evaluation has been used in similar research [26,27,30,31]. The models were either from previous group projects (see [[53], [54], [55]]) or downloaded for free from Sketchfab. All models met the software requirements: polygonal 3D models with quad-based topology and primarily texture-based materials. *Fig. 3* shows an image of each model with its identification number and LoD score. The complete result of the analysis of these models with LoDCalculator can be found in *Annex I* hosted in the repository.

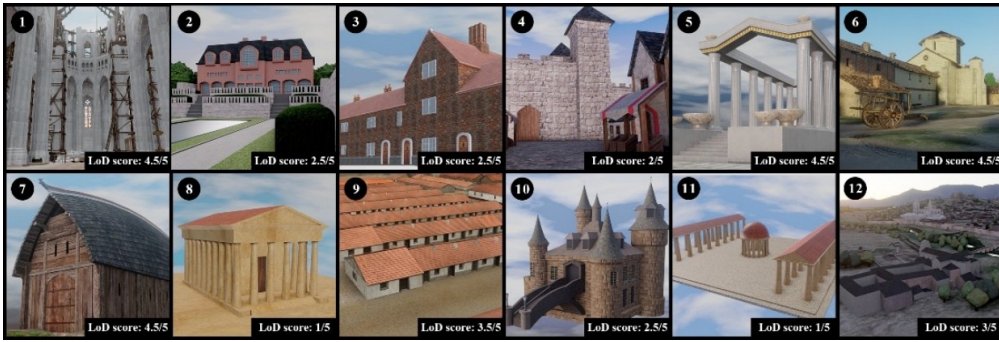


Fig. 3 Images of the 12 3D models analyzed with LoDCalculator, their identification number at the top left, and their LoD score at the bottom right of each image

On the one hand, Fig. 4 presents the study results with a scatter plot illustrating the relationship between software scores (X-axis) and evaluator's Mean (M) scores (Y-axis) of each model, separated into the student group (green) and professional group (orange). The data have a slight jitter for better visualization. Each score is surrounded by a circle of purple dots with a radius equal to half the distance between scores, indicating the influence area of each score. Data points outside these circles represent outliers. Fig. 4.1 shows geometric fidelity data, Fig. 4.2 shows radiometric fidelity data, and Fig. 4.3 shows the LoD score data. On the other hand, Table 2, Table 3, and 4 present the scores given by the software and the M scores of both groups of evaluators along with their Standard Deviation (SD), with Geometric Fidelity represented in Table 2, Radiometric Fidelity in Table 3, and the LoD Score in Table 4. Finally, Table 5 presents the results of the correlation analysis conducted. Correlation analyses have only been performed on sets of models, as the software score per model does not vary. The ρ have also been extracted from the dataset of both groups. All the data is available in Annex I.

Table 2. Geometric Fidelity results. For each model the LoDCalculator score, and the M and SD scores of the Student and Professional group are shown

Model Number	LoDCalculator score	Student group (M/SD)	Professional group (M/SD)
1	3	2.98/0.16	2.85/0.37
2	2	2.05/0.44	1.65/0.59
3	2	1.49/0.60	1.60/0.50
4	1	1.34/0.53	1.20/0.41
5	3	1.87/0.68	2.15/0.49
6	3	2.85/0.42	2.75/0.44
7	3	2.39/0.59	2.60/0.60
8	1	1.05/0.22	1.10/0.31
9	2	1.95/0.44	1.95/0.60
10	2	2.17/0.54	1.75/0.64
11	1	1.07/0.26	1.15/0.37
12	2	1.88/0.64	1.75/0.55

Table 3. Radiometric Fidelity results. For each model the LoDCalcualtor score, and the M and SD scores of the Student and Professional group are shown

Model Number	LoDCalculator score	Student group (M/SD)	Professional group (M/SD)
1	2.5	2.63/0.39	2.65/0.33
2	1.5	1.87/0.43	1.48/0.41
3	1.5	1.49/0.41	1.40/0.35
4	2	1.95/0.48	1.73/0.60
5	2.5	2.80/0.31	2.63/0.46
6	2.5	2.76/0.28	2.55/0.46
7	2.5	2.54/0.39	2.25/0.47
8	1	1.05/0.15	1.33/0.29
9	2.5	2.23/0.45	2.35/0.40
10	1.5	1.77/0.39	1.63/0.51
11	1	1.21/0.30	1.23/0.26
12	2	1.95/0.56	1.90/0.55

Table 4. LoD Score results. For each model the LoDCalcualtor score, and the M and SD scores of the Student and Professional group are shown

Model Number	LoDCalculator score	Student group (M/SD)	Professional group (M/SD)
1	4.5	4.24/0.68	4.53/0.50
2	2.5	2.60/0.78	2.15/0.65
3	2.5	1.87/0.75	1.95/0.63
4	2	2.46/0.79	2.23/0.85
5	4.5	3.91/0.86	3.85/0.78
6	4.5	4.41/0.67	4.28/0.73
7	4.5	3.93/0.88	3.68/0.80
8	1	1.22/0.35	1.50/0.51
9	3.5	3.23/0.77	3.40/0.79
10	2.5	2.55/0.67	2.45/0.90
11	1	1.39/0.44	1.43/0.52
12	3	3.21/1.06	2.85/0.95

Table 5. Correlation analysis between the scores of each evaluation group and both groups with the scores of the software in each of its punctuations. For each correlation the Pearson and Spearman coefficients are shown

Scores	Student group (Pearson ρ /Spearman ρ)	Professional group (Pearson ρ /Spearman ρ)	Both groups (Pearson ρ /Spearman ρ)
Geometric fidelity	0.671/0.669	0.727/0.729	0.689/0.688
Radiometric fidelity	0.785/0.787	0.732/0.749	0.766/0.773
LoD Score	0.795/0.788	0.778/0.790	0.792/0.788

Figure 4.1 Geometric fidelity results

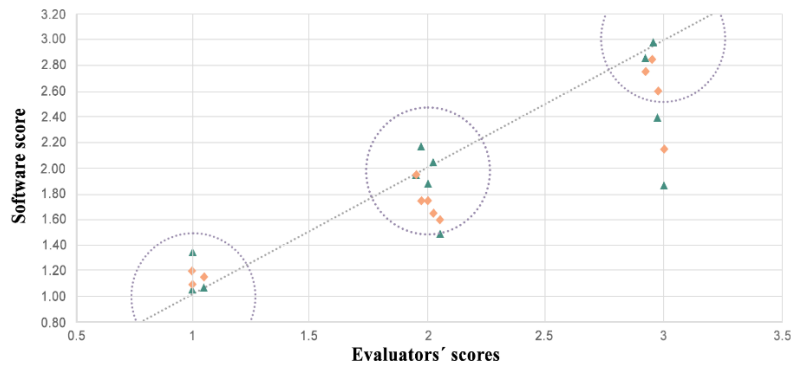


Figure 4.2 Radiometric fidelity results

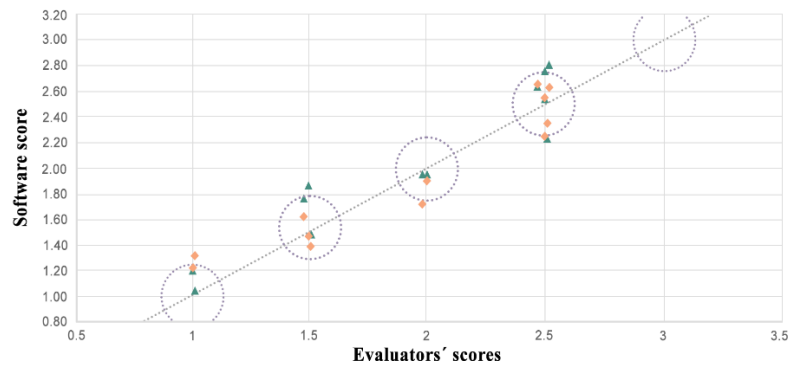


Figure 4.3 LoD score results

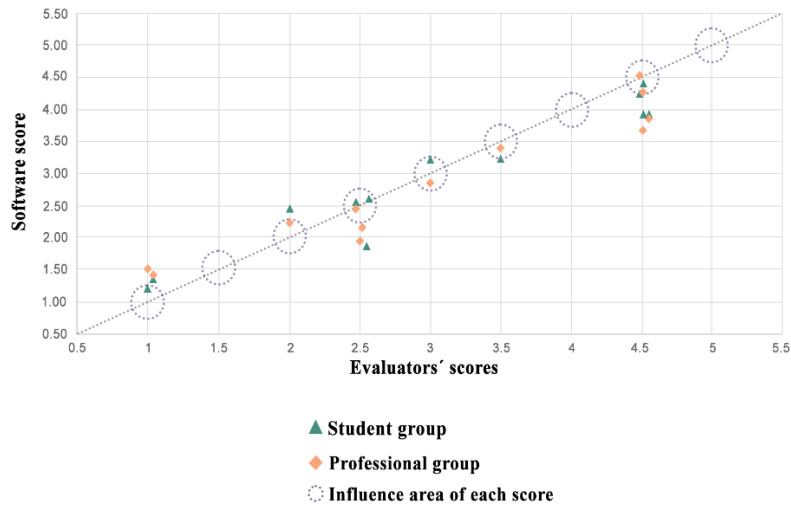


Fig. 4 Evaluation results in scatter plots (M) separated by student group and professional group. Fig. 4.1 shows the geometric fidelity results, Fig. 4.2 shows the radiometric fidelity results, Fig. 4.3 shows the LoD score results

Overall, there was a strong similarity between the sample results and those of the software, except in the extreme scores, where the lack of higher or lower ratings caused the M to diverge. Additionally, except for a few models, the SD were low, indicating a high consistency in the results. In that sense, there were few outliers, with Model 5 having the most divergences followed by Model 7 and 3, though with less noticeable differences. These models are distinguished by higher material complexity, with Models 5 and 7 transferring much of their geometric complexity to normal maps [56], which may have confused the evaluators by mixing geometric and material complexity. Model 3, with its excessively tiled textures, might have also affected perception, especially for less experienced students [11]. It had already been considered that such differences might be harder to assess. Although the software is quite general, greater emphasis and precision were placed on radiometric analysis for this reason. Nonetheless, slight deviations may still arise in more complex models. Outliers that slightly increased the LoD score might be due to the increased complexity of the general analysis of the model and the greater number of options available to the user. Furthermore, the models were large and complex, composed of many parts, which could affect the evaluators' perception. However, the intended purpose of the software was, after all, to analyse complex models and environments. Considering the correlation coefficients, a strong level of agreement was achieved, around 0.750, which is notable for a general-use software like this. The coefficients were slightly lower for students' geometric fidelity, although they were still above 0.670. In all likelihood, it was due to the smaller number of options available to the user in these scores. However, the total ρ in LoD score was almost 0.800, showing a strong relationship. It may also be observed that the professional group was more critical of the models, which could be explained by the novelty effect experienced by the students during the task [57]. In a deeper analysis, it can be observed that junior professionals, despite having a similar perception to seniors, rate the 3D models more positively, indicating that the novelty effect also influences them.

Compared to other experiments validating LoD classification through subjective evaluations [30,51,58], this research features a comparable sample size, with around 50 subjects being common. However, it differs by classifying different 3D models, rather than versions of a single model. Additionally, this research stands out for including subjects with experience in the field, categorized by their expertise. The results are aligned with those of other studies when LoD is evaluated in controlled conditions [58], but in more interactive environments, evaluators tend to have difficulty to differentiate LoD accurately [30,51]. A limitation of this study is the lack of comparative analysis with other classification methods, as the diversity of 3D models and the type of analysis executed are not directly comparable to other measurement methods, typically used for point cloud or distortions analysis [58].

4. Impact

The classification and evaluation of LoD is crucial in 3D model development, as it impacts development time, costs, and enables better management of computational resources on devices, particularly low-resource ones like iVR [33]. However, existing systems have several limitations hindering their widespread use. On one hand, some semantic classification systems lack sufficient guarantees for universal comparisons, are open to broad interpretations, present usability challenges, or have proprietary costs. On the other hand, many studies focus on analysing distortions and complexities of various versions of point clouds or other 3D elements, which are not suitable for video game development, such as iVR [40].

LoDCalculator addresses the need for a universal LoD analysis that is comparable across multiple 3D modelling contexts in an accessible and free manner. This is particularly useful for teams with limited 3D modelling experience due to its user-friendly interface and easy-to-understand results [45]. It is especially valuable in multidisciplinary fields like iVR, where research teams with limited computing expertise often venture into iVR development to broaden their outcomes. Fields such as education and CH dissemination, where iVR is an emerging technology, particularly benefit from this [59]. This research provides a tool that can serve as a common framework for LoD classification, helping to streamline 3D modelling development processes and generating a significant positive impact in these areas, which often lack the resources and experience of industry or engineering [12]. Furthermore, LoDCalculator works through Blender, an open-source 3D modelling suite and one of the most widely used software tools for such purposes [44]. LoDCalculator was tested in that field, yielding good LoD assignment results that were reasonably well aligned with the results of the evaluation group, showing that it is a tool with reasonably accurate results for these purposes.

5. Conclusions

The use of LoD in 3D modelling projects is crucial, although current tools for classifying 3D models by LoD have limitations that hinder their widespread use. The LoDCalculator, an add-on for Blender, developed with the Blender Python API, has been used to address these issues. It features: 1) mathematically defined, unambiguous thresholds; 2) universal analytical capability for the analysis of any model regardless of scale or PC; and 3) system accessibility, integrated into one of the most widely used open-source 3D modelling software with a user-friendly interface. Its main limitation is that it may not be fully suitable for non-realistic 3D models, due to the parameters it applies for generalized analysis. However, its thresholds can be easily modified for customized use. Comparing the software's

criteria with professional and semi-professional users in the analysis of 12 3D models showed a comparable performance to the sample criteria. It is therefore a valuable tool for assessing the LoD of 3D models, especially in multidisciplinary environments, due to its ease of use and integration in the modelling software.

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This publication complements *Result 2* by addressing the creation of 3D models for virtual CH reconstruction and their implementation in iVR experiences to foster immersion and presence. To achieve this, it proposes a procedure for modeling, optimizing, and validating 3D models for this purpose; with particular emphasis on the development of virtual agents, highlighting both their advantages in CH dissemination and the greater challenges involved in their creation. The selected case study is one of the key pieces of the Museum of Burgos: the Roman sculpture of the goddess Isis from the roman city of Clunia Sulpicia. This research was conducted in collaboration with the University of Salento, the host institution for the PhD student during their international research stay.

The outcomes of this study complement previous results by providing comprehensive tools to optimize the development of 3D models for CH reconstruction: 1) an add-on for the straightforward classification of LoD; and 2) a procedure to generate, optimize, and validate 3D models for CH reconstruction. Moreover, the 3D model created was used in a pilot iVR validation, which serves as a starting point for Goals 3 and 4. This result is aligned with Goal 2. *Table 5* presents the bibliometric data of this publication.

Table 5. Bibliometric data of Result 3

TITLE	The Virtual Reconstruction of a Statue of Isis unearthed at the Roman City of Clunia (Spain): a 3D Model for Interactive Virtual Reality Experiences
STATE OF PUBLICATION	Peer review (Minor revisions submitted on 22/09/2025)
JOURNAL	Journal on Computing and Cultural Heritage
DATE	2025
JCR	Q3 Computer Science, Interdisciplinary Applications (2023 release)
DOI	Not applicable
AUTHORS	Bruno Rodriguez-Garcia, Laura Corchia, María José Zaparín Yáñez, Lucio Tommaso De Paolis
KEYWORDS	3D modeling, Virtual Reality, Cultural Heritage, Virtual Reconstruction

THE VIRTUAL RECONSTRUCTION OF A STATUE OF ISIS UNEARTHED AT THE ROMAN CITY OF CLUNIA (SPAIN): A 3D MODEL FOR INTERACTIVE VIRTUAL REALITY EXPERIENCES

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Abstract. This research aims to contribute to the advancement of technologies applied to the conservation, reconstruction, and dissemination of Cultural Heritage, such as photogrammetry, 3D modeling, Virtual Agents, and Virtual Reality. To this end, the virtual reconstruction process of a Roman alabaster sculpture of the Goddess Isis is presented and assessed in a comprehensive and systematic procedure. Unearthed at the Roman city of Clunia (province of Burgos, Spain), the sculpture dates back to approximately the 2nd c. AD. The virtual reconstruction depicts both existing and missing features, based on the remains and comparisons with other extant representations of the goddess. The generated 3D model was designed to function as a Virtual Agent in interactive experiences. Moreover, discrepancy, detail and vertex concentration analyses of the model yielded satisfactory results. The visualization of the 3D model was tested in an interactive Virtual Reality experience at the Museum of Burgos with 60 participants, whose evaluations were highly positive. Clustering of participant responses revealed behavior patterns that were primarily associated with age and previous experience with Virtual Reality. The 3D model of the virtual reconstruction is open access and free to download.

1. Introduction

New technologies are increasingly present today and are gaining significant importance within the field of Cultural Heritage (CH) [9], due to their various functions. There are, on the one hand, applications that facilitate the analysis and the conservation of CH [62], assisting work procedures and process documentation [58]. For example, 3D modeling [20], photogrammetry [45], and laser scanning [49] are all now virtually essential in archaeological reconstructions [28]. Such technologies can be used to collect and to process the data needed for virtual reconstructions [76], resulting in a hypothetical 3D view of a CH site or artifact in its original state [31].

On the other hand, there are also new technologies that can serve as tools for the dissemination of CH [47], particularly eXtended Reality (XR) technologies [26], a heading that covers Augmented Reality (AR), Mixed Reality (MR), and Virtual

Reality (VR) [10]. Although first used in the CH field in the 1990s [38], their use has gained greater interest within the public domain over the past decade [10]. AR has accompanied the rise of smartphones and the launch of Oculus DK1 has significantly advanced the use of VR [17]. VR has since become widely recognized in its immersive form (iVR), unlike VR, the iVR environment completely envelops a user, perhaps equipped with a Head Mounted Display (HMD) or a Cave Automatic Virtual Environment (CAVE) system [5]. The dissemination of CH through XR technologies, such as iVR, can improve knowledge transmission, especially spatial information [18], by enhancing the clarity of archaeological data and hypothetical visualizations. It can also improve user satisfaction [1], whilst contributing to CH preservation and accessibility [66].

The widespread acceptance of the above-mentioned set of new technologies in the field of CH has seen their introduction alongside traditional musealization experiences [94]. For example, XR has had a significant impact on knowledge transmission [4]. Now integrated in what are known as Virtual Museum (VM) experiences, these digital museum-like experiences also serve to digitize entire collections [93]. VM bridges geographical boundaries and promotes remote access [88]. In this sort of musealization experience, the use of Virtual Humans (VH) or Virtual Agents (VA) is common [85]. Interactive or otherwise, they guide users through the virtual environment [55]. As agents within a virtual environment, they transfer knowledge of intangible heritage and act as virtual guides [55]. In brief, the inclusion of a VH or a VA enhances user satisfaction and assists knowledge transmission [46].

This research aims to contribute to the advancement of technologies applied to the preservation, reconstruction, and dissemination of CH, such as 3D modeling, photogrammetry, and iVR within high-impact contexts such as museums. To this end, the research presents a case study in which these technologies are comprehensively and systematically implemented through the virtual reconstruction and validation process of a Roman sculpture of the goddess Isis, unearthed at the Roman city of Clunia (Spain). For this purpose, a qualitative approach was employed for the historical reconstruction and a mixed qualitative and quantitative approach for assessing the 3D model. The resulting 3D model is designed to function as an open-access downloadable VA ready to use in other iVR experiences. Furthermore, this model has been integrated into an immersive iVR experience, which was validated within a real musealization environment.

The structure of the paper is as follows. In *Section 2*, related works are analyzed, and the novelty of the study is emphasized. In *Section 3*, the characteristics of the case study, a Roman statue of Isis, are described. In *Section 4*, the reconstruction and validation procedure of the 3D model is detailed. In *Section 5*, an explanation of the

development of the iVR experience used to test the 3D model is given. In *Section 6*, the evaluation process of the iVR experience and its results are detailed. Finally, the conclusions of the study are presented in *Section 7*.

2. Related work

The virtual reconstruction of statues has been addressed in scientific literature. The state of conservation of a statue determines the process that is followed. On the one hand, if in good condition and intact with no need for further restoration, restoration will typically be focused on its original polychromy. On the other hand, a full or partial reconstruction of a statue in a poorer state of preservation with one or more missing features is usually undertaken.

Various restoration projects have been described in the literature. For example, the restoration of the Lingyan Temple (China) statues, dated between the 11th and the 14th c., whose original polychromy was restored [86], and the sculptures in the Dunhuang Mogao Grottoes (China) where non-rigid transformation was tested for better reproduction of the original textures [97].

Moreover, anastolysis or structural and non-structural reconstruction is necessary when a statue is not well conserved. The anastolysis reconstruction technique involves the reassembly of separate parts to recreate an original piece [21]. One example is the reconstruction of Roman masks found on the island of Lipari (Italy) dating back to the 4th c. B.C., whose reconstruction, after photogrammetry, involved joining their different parts together [57]. However, a reconstruction may also be partially based on anastylosis and combined with other reconstruction techniques, such as the restoration of the statues from the Temple of Zeus at Olympia (Greece) from the 5th c. B.C., for which structural and non-structural reconstruction was used [69]. If anastylosis is not an option, structural and non-structural elements can be reconstructed upon the basis of documentation and comparison with similar artifacts. Examples include the 2nd c. statues of Aesculapius and Hygeia at the Sanctuary of Isis in Lilybaeum (Italy), which were reconstructed using other sculptures as documentation [29], or the circa 1st and 2nd c. AD lion sculptures, respectively, at the Lapidario Estense Museum and at Modena Cathedral (Italy), both also reconstructed using the same method [33]. In some cases, only specific missing components of the sculptures required reconstruction, such as the weapons of the 12th c. Ni-Tennō statues (Japan) [83].

Additionally, some of these reconstructions have been evaluated through XR experiences, such as AR or iVR, to assess the effectiveness of the work in a real dissemination environment. For instance, the reconstructions of the two lions, one at the Lapidario Estense Museum and the other at Modena Cathedral, were tested

with an AR application [34], while the reconstructions of the weapons of the Ni-Tennō statues were evaluated through an iVR experience [83].

However, statue reconstructions for the purpose of a VA are relatively uncommon. Typically, a VA (or VH) in a CH experience is used for three main purposes. It first of all serves as an inhabitant of the virtually reconstructed environment [55]. A VA will often serve to convey certain concepts of intangible heritage while also enhancing the realism and immersion of virtual reconstruction. One example is the case of the virtual reconstructions of Mesopotamia circa 5000 B.C. [87] and a pre-Columbian Amazonian village [27], which both used a VA depicted as an indigenous inhabitant of the reconstructed site. Second, a VA can be used to provide instructions or tasks in more complex experiences with challenges. Some examples are the reconstruction of Little Manila in the 20th c. [90] and the Temple of Hera, circa 500 B.C. [68]. Finally, a VA is frequently used as virtual guide to help users understand different parts of the iVR experience, as featured in the reconstructions of the City of Uruk, circa 3000 B.C. [11], the Great Palace of Knossos, circa 1700 B.C. [43] or the iVR experience about the city of Heraklion (Greece) [2] and the iVR experience of the Museo Egizio of Turin (Italy) [12].

Although these studies have significantly contributed to the advancement of this discipline, no research has focused on integrate these outcomes into a systematic and comprehensive process that combines the data acquisition, restoration, optimization, and validation of a statue to produce a 3D model with VA capabilities, ready for use in iVR experiences. In addition, this research evaluates the resulting 3D model through a pilot iVR experience conducted at the Museum of Burgos, involving a highly diverse age group. The outcomes revealed distinct behaviors patterns, identified through a clustering analysis of the participants.

3. Case study: Statue of Isis of Clunia

The sculpture of the Isis of Clunia was unearthed in an area adjacent to the theater, a major archaeological site located at the ancient Roman city of Clunia to the south-east of the province of Burgos (Spain) [8]. Various theories on its original location have situated it among the sculptures around the theater, as shown in *Figure 1.1* [60]. The worship of this deity, the mother of Horus, survived assimilation into both the pre-existing Greek and Roman pantheons. As Rome's conquests spread, the gods and goddesses of other cultures were often renamed after existing Roman divinities, although the worship of the goddess Isis continued throughout the Hellenization of Egyptian culture and subsequent Romanization, slowly spreading through Italica into Hispania. The expansion of the cult of Isis during the reign of the Emperor Hadrian has been linked to maritime trading and the status of major cities that would

require at least one temple for her adoration [6]. So, the goddess unearthed at Clunia, rather than a typical representation of ancient Egypt, was depicted in the Hellenic style that emerged in Alexandria during the Ptolemaic dynasty of Egypt [95].

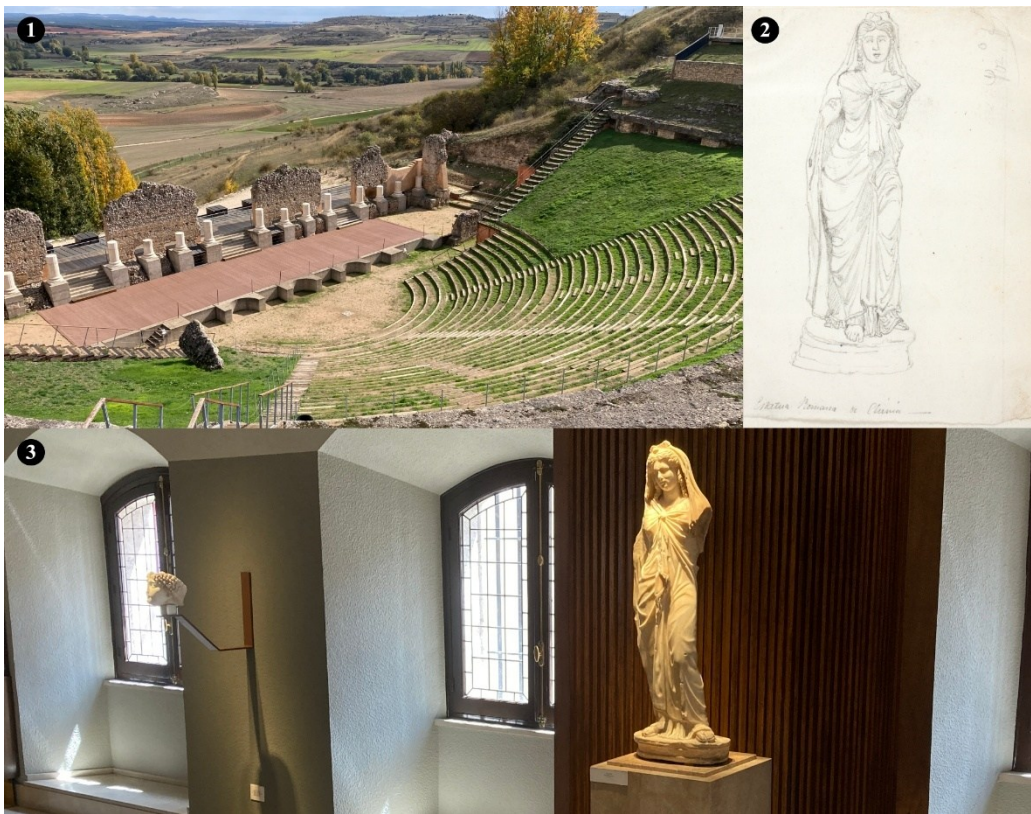


Fig. 1 1) Archaeological site of the theater of Clunia; 2) Cecilio Pizarro “The goddess Isis (Clunia)” compound pencil, 113 mm x 82 mm (D006404/111-04, Madrid, Museo Nacional del Prado, © Archivo Fotográfico Museo Nacional del Prado); and 3) statue of the Isis of Clunia at the Museum of Burgos

The news of its discovery was documented in an article published by Salomón Remigio in a weekly magazine in 1853 [80], accompanied by a woodcut print of a drawing by Cecilio Pizarro, now conserved at the Museo Nacional del Prado, Madrid (D006404/111-04 [64]), as shown in Figure 1.2. The statue had been found the previous year by Santiago Lucas, in a horizontal and slightly inclined position. A plaque dedicated to the Emperor Hadrian was found nearby: 'To the health of Emperor Caesar, Augustus Hadrian, of the Cluniense Colony' [80], five columns, three small bronze wings, some ceramics, fragments of ivory, and deer antlers [3].

The sculpture of the goddess Isis at Clunia, dated to the 2nd c. AD, rests on a small oval pedestal with a double toroidal profile. Standing at a height of 1020 mm,

it was sculpted in a naturalistic style, reflected in an elegant and sensual contrapposto, with the weight of the body resting on the right leg. This creates a sinuous silhouette, with its feminine forms accentuated by the draping of the garments fitted to the chest, abdomen, and thighs. Beneath the tunic, the folds of an undergarment are visible, revealing feet shod in sandals. The shoulder-length headdress defines the oval shape of the face around which curled strands of hair are still visible on either side. One detail that clearly identifies the sculpture as a depiction of the goddess Isis is the presence of the aforementioned Isiac knot [95]. A sign reinterpreted, in the Greco-Roman manner, known for its protective properties [6]. There are also some remnants upon the headdress that could be vestiges of crescent moon [80]. Both arms of the statue are missing, along with the left and the right hand that would in all likelihood have held a situla or ritual pitcher, and a sistrum, an ancient rattle of metal rods, respectively [6]. *Figure 1.3* shows the sculpture at the Museum of Burgos (Inv. 27 [71]), its current location.

The analysis of the statue was supplemented by a comparative study of other Roman representations of the same deity, to facilitate the reconstruction process. The missing elements that might further define its iconography could in that way be interpreted on the basis of reliable sources. To do so, sculptures were selected according to their similarity in terms of their state of preservation, arrangement, posture, and other features that might assist with the virtual reconstruction. Among various works, the statue of Isis from the Capitoline Museum in Rome (Inv. Scu 744 [82]), was selected. Although significantly larger than the sculpture unearthed at Clunia, it shares important similarities with its Spanish counterpart. The Capitoline statue (displayed in *Figure 2.1*) holds a sistrum aloft in its right hand, while the situla hangs loosely below the waistline in the left hand [6]. It should be mentioned that the sculpture has undergone restoration in modern times.

The sculptures from the Museum of Art History in Vienna (Inv. 1-158 [65]), *Figure 2.2*, and the Museum of Naples (Inv. 6368 [35]), in *Figure 2.3*, are also of interest, especially as parts of their polychromic coating are still in place. However, the former only showed the handle of the sistrum, the instrument itself having been lost to posterity. Both works and the Capitoline Isis have a headdress partially covering the side of the face crowned with a solar disk, although without the crescent moon diadem upon the Clunia sculpture that is likewise no longer with us. It was therefore logical to search for such distinctive symbols on other statues. One example was found at the National Roman Museum of the Baths of Diocletian [36] in Rome, shown in *Figure 2.4*. Here, the lunar horns support the solar disk, although without a headdress. In that way, examples of all the distinctive iconographic symbols no longer part of the sculpture under reconstruction could be assessed.



Fig. 2 Isis statues: 1) Capitoline Museum, Rome (Image by © Sailko, licensed under CC BY 3.0, available on Wikimedia Commons [79]); 2) the Museum of Art History, Vienna (Image by © Marcus Cyron, licensed under CC BY-SA 2.0, available on Wikimedia Commons [56]); 3) Museum of Naples, Naples (Image by © Gryffindor, licensed under CC BY 2.5, available on Wikimedia Commons [37]); 4) National Roman Museum of the Baths of Diocletian, Rome (Image by © Carole Raddato, licensed under CC BY-SA 2.0, available on Pinterest [13])

4. 3D model development and assessment

The reconstruction process is summarized in *Figure 3*, in the same order as *Sub-section 4.1. Reconstruction procedure*. The purpose of this procedure is to achieve a faithful reconstruction of the historical-archaeological documentation described in the *preceding Section*, to obtain a realistic 3D model that could be used as a “game-ready” asset in a game engine. Due to this and considering that the reconstruction process significantly alters the appearance of the piece, this procedure has prioritized optimization over the preservation of a ground-truth surface. Subsequently, the validation procedure applied to the resulting 3D model will be detailed in *Sub-section 4.2 Model Assessment*. The 3D model in .fbx format can be consulted and downloaded in *Annex I*.

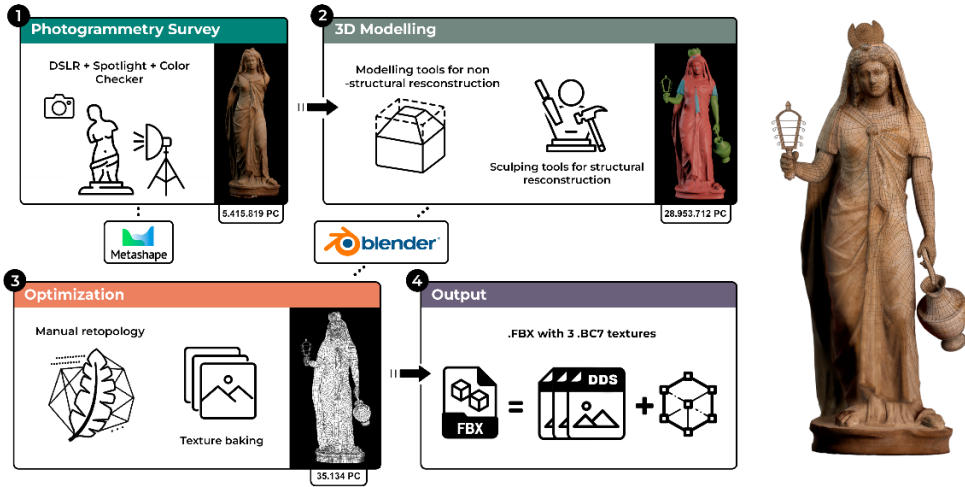


Fig 3 Summary of the reconstruction procedure

4.1 Reconstruction procedure

A photogrammetric survey was the first step of the reconstruction procedure. In this case, the photogrammetric survey of the statue served as the basis for the subsequent introduction of all the secondary documentation described in the *preceding Section* [40]. A procedural phase that is summarized in *Figure 3.1*.

A conventional low-cost set of instruments was used for close-range photogrammetry, as described in several works [42, 52]. The instruments were a Fujifilm X-T20 Mirrorless DSLR camera equipped with an APS-C sensor of 24 megapixels. Additionally, two diffuse light sources were employed to compensate for the ambient lighting conditions of the museum, as shown in *Figure 1.3*. A Calibrate Color Checker Passport Photo 2 was also used to perform white balance calibration and ensure accurate color capture. This calibration target includes a reference square of 50 mm, which was used as a scale reference for the photogrammetric model. Image capture was configured with a focal length of 33 mm (equivalent to 50 mm on a full-frame sensor), ISO 640, an aperture of F/6.4, and a shutter speed of 1/30 s. These capture parameters remained consistent throughout the acquisition process, which is a key factor for the successful development of the image data acquisition phase [81]. The chosen specifications aimed to maximize image homogeneity and minimize noise, taking into account the museum's lighting conditions. A total of 193 images were captured in RAW format at a resolution of 6000×4000 pixels. The quantity and resolution of the images are comparable to those used in other datasets for image-based 3D reconstruction [48], providing a high degree of overlap between frames, an essential factor for the successful generation of the photogrammetric model [73].

Photogrammetry was selected as the acquisition method for several reasons. First, it is the most widely used and accessible technique, which not only aligns with the team's prior experience but also enhances the replicability of the workflow in future studies [74]. Second, while other acquisition methods may offer higher geometric accuracy, photogrammetry excels in capturing high-quality color and texture information, making it one of the most popular techniques in archaeological documentation [51]. Moreover, in subsequent stages of the procedure, texture quality will be prioritized over surface fidelity to optimize the model, as it represents one of the most critical aspects in the optimization of 3D models, since much of the simplification of the 3D model occurs at the surface level [23]. Consequently, the deviations introduced by photogrammetry, are potentially in the range of a few millimeters under suboptimal conditions [74].

For image processing, Agisoft Metashape was selected, with which the research team was familiar and that is widely used in photogrammetry projects [45]. Upon completion of this phase, the 3D model contained a Polygon Count (PC) of 5,415,819 triangles. Handling such a dense mesh in the subsequent stages of the workflow may be computationally demanding, particularly for devices with limited hardware resources. An alternative approach would be to generate a lighter, optimized mesh directly within the photogrammetry software. However, this would result in a less accurate model.

Subsequently, the historical-archeological information detailed in *Section 3* was incorporated into the photogrammetric model to complete the missing parts of the sculpture. A summary of that phase in the procedure is shown in *Figure 3.2*. To do so, two different methods were followed. Firstly, digital sculpting was used to reconstruct elements requiring structural restoration, such as the statue's nose. The choice of that technique was because it enables easy modification of such elements as the body of the sculpture. Secondly, 3D modeling was employed to reconstruct parts that needed non-structural restoration, such as the situla and sistrum, held in the left and the right hand of the reconstructed statue, respectively. The 3D models generated in this phase were created entirely from scratch. This procedure was selected rather than using photogrammetric models as a base, for the following reasons. Firstly, due to the geographical and administrative challenges involved in capturing photogrammetric data of the other statues located in different museums. Secondly, the varying sizes and poses of the other sculptures would have required adaptations regardless, limiting their usefulness as direct references. Likewise, their development was based on the historical-archeological information presented in *Section 3*, and the process underwent several rounds of review by history of art experts. The 3D modeling was utilized because it is often used to create geometric models from scratch.

Then, using the digital sculpting tool, some of the reconstructed parts, such as the arms and the crown, were merged with the photogrammetric model. Following a working principle of restoration that restored parts should be visibly distinguishable, a slightly different material was used for the reconstructed parts. This material was created by cloning the preserved parts of the sculpture. The entire phase was carried out using Blender 3D modeling software, version 3.6 Long Term Support (LTS). Blender was chosen, as it is an open-source software, making it one of the most popular CH research software packages [47]. Additionally, the research group has gained experience with that software in other CH modeling projects [18]. Other widely used software solutions for these purposes include Cinema 4D, 3D Studio Max, and Maya; however, their high cost represents a significant limitation for many research and development contexts [77]. Upon completion of that phase, the 3D model contained a total of 28,953,712 triangles. The use of the digital sculpting tools with the photogrammetry-based model explains the higher PC, as it was configured to modify the topology of the 3D model by generating additional polygons. Topology alteration is a recommended process to preserve the surface of the photogrammetric model, since not generating new polygons would require repositioning the existing ones, thus modifying the shape of the piece. However, this drastic increase in PC can lead to performance issues on low- and mid-range computer systems.

The results of both phases of the procedure are illustrated in *Figure 4*. Firstly, the photogrammetric 3D model is shown (*Figure 4.1*), followed by the completed reconstruction (*Figure 4.2*), and finally, the Extended Matrix archaeological evidence scale (*Figure 4.3*). Extended Matrix and its toolkit are designed for virtual heritage reconstruction and transparency [21]. In this project, the various sources used in the reconstruction were checked against the Extended Matrix properties scale. The properties of an artifact are classified in eExtended Matrix, although all levels of evidence not used in this reconstruction were omitted, is shown to the left of *Figure 4.3*. The color coding of the scale refers to: 1) the extant parts (generated through close-range photogrammetry) in red; 2) the structural reconstructions (generated through digital sculpting) in blue; and 3) the non-structural reconstructions, based on the documentation detailed in *Section 3* (generated through 3D modeling) in green. The visualization of such data is of great importance in the CH domain, as transparency is one of the fundamental principles of the London Charter [22].



Fig. 4 Reconstruction phases: 1) photogrammetric model; 2) reconstructed model; 3) scale of archaeological evidence

Finally, the reconstructed model was optimized, so that it was ‘game-ready’, and its functions could be seamlessly incorporated into a game engine. It involved a common optimization process for using a model in game engines [84], by reducing both the number of vertices and the number of textures and materials used in the model, as 3D model generation processes based on photogrammetry typically result in a very high number of triangles [30]. This process is crucial for the proper functioning of 3D models in interactive environments, but particularly in iVR, due to the more limited resources available on these devices [16]. In addition, in this project the optimization process ensured that the model could be used as a VA. This process necessarily involves a simplification of the 3D model’s surface, although its visual appearance will be preserved. For this reason, it is preferable to use a data acquisition method that excels at preserving textures, as these will not be simplified during the optimization process. Moreover, textures play a key role in visually conveying part of the geometric detail lost during simplification [23]. This process, therefore, constitutes a trade-off between surface fidelity and ensuring usability in interactive environments [72]. This phase of the procedure is summarized in *Figure 3.3*.

First, the number of the 3D model vertices was reduced through retopology, a process that remodels an existing 3D model with a mesh that has fewer polygons than the original model [61]. Typically, the process is performed in the CH domain using automatic retopology tools, such as those available in Z-Brush or Blender [25]. Their results are satisfactory, but a sufficient level of adequacy for more complex contexts, such as animation, is not achieved [14]. In this work, a manual retopology

procedure using the Blender modeling toolkit was carried out, in a process through which all the polygons of the new (Low-Poly) model were manually generated and connected, while maintaining the shape of the reference (High-Poly) model. Manual retopology permits a drastic reduction in the number of triangles (5,415,819 vs 35,134), thereby enabling a mesh of polygon loops to recreate the 3D shape in future animations.

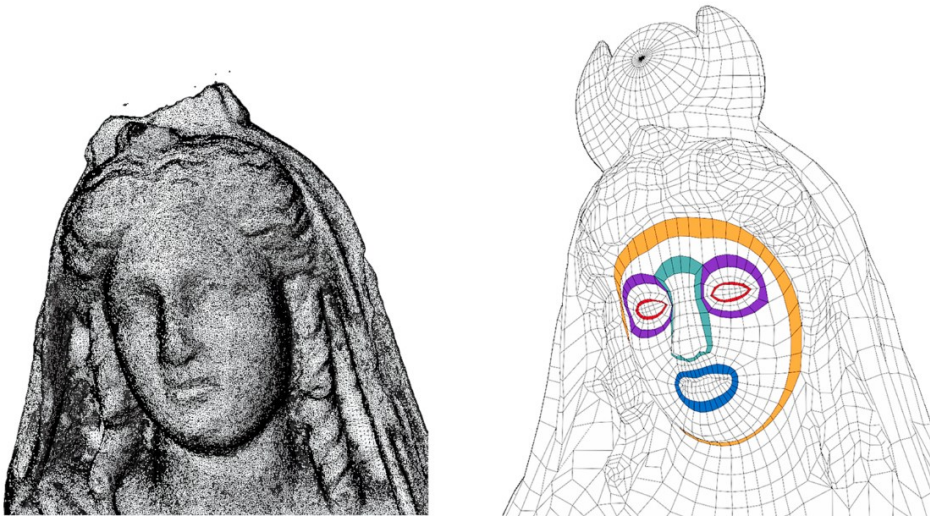


Fig 5 Face mesh from the photogrammetry model (left); face mesh of the retopologized model with some of its edge loops marked in color (right)

An edge loop is a continuous line of polygon edges that loops around a mesh to connect with itself, forming a complete loop. The placement of edge loops is a very important factor in model deformation and the loops play a fundamental role in 3D model animations, which rely on mesh deformation to generate new shapes [20]. The flow and the loops of the Low-Poly model were designed to follow the anatomical shapes of the sculpture, so that the mesh deformations seemed to be as natural as could be. Additionally, the polygon flow was aligned, in so far as possible, with the wet drapery effect of the clothing on the asymmetrical posture of the statue, while ensuring connectivity with the other loops. Finally, a higher density of polygons was concentrated in areas with multiple joints (i.e., the hands) to reflect movements of greater complexity. An example of the use of edge loops on the face of the sculpture is shown in *Figure 5* where the photogrammetric mesh is shown on the left, and the retopologized mesh, on the right. The left-hand side of the figure shows some of the most important loops, such as the eyes, the nose, the mouth, and the face, which are traced out with colored lines. Movements reflecting contraction and expansion of, for example, facial features can be achieved with the polygon structure in those areas, lending greater expressiveness to the 3D model. This aspect

is particularly important when creating models intended for animation, as in the case of a VA. For a non-interactive model, automatic retopology could be used, which would simplify the process. However, this approach requires significant prior experience in 3D modeling to be carried out effectively. Upon completion of that phase, the 3D model was composed of 35,134 triangles.

Finally, all the details from the High-Poly model were transferred to the Low-Poly model through baking and texture reprojection. Both techniques are widely used procedures in projects with similar retopology workflows [67]. In that way, geometric details of a 3D model may be transferred to a texture, resulting in significant PC savings [15]. To do so, a cage model that enveloped both the High and the Low-Poly models was created, serving as a spatial reference for texture reprojection. The cage must encompass both models and as accurately as possible resemble their shapes for the process to function properly. In this study, the cage properly enveloped both models after modifying the Low-Poly model. The entire Low-Poly model was unwrapped to reduce the number of textures and so that it occupied the full UV space. Additionally, Physically Based Rendering (PBR), which combines various textures that simulate the physical properties of an object [23], was used to create material textures with realistic reactions to any type of lighting. It is a key feature for enabling a 3D model to be incorporated into a wide variety of photorealistic environments. A total of 3 textures were created with the standard PBR methodology:

- *Diffuse texture*: a Red, Green and Blue (RGB) texture that encodes information on model colors, disregarding specular reflection [96]. The final texture was generated by reprojecting the diffuse texture of the High-Poly model onto the UV space of the Low-Poly model.
- *Normal texture*: an RGB texture that encodes the direction of surface normal vectors using the RGB channels for each axis [70], so that non-existent geometry may be simulated. The normal texture was generated by baking the geometry of the High-Poly model.
- *Roughness texture*: a Black and White (BW) texture that contains information on the degree of dispersion that light should adopt when in contact with the object [24]. The texture was generated with the Blender rendering engine that calculates material roughness.

A metallic texture can also be created to distinguish metallic properties [44], though it was unnecessary in this reconstruction with no metallic parts. The entire process was completed with the Blender modeling toolkit. This process could also be carried out using software such as Adobe Substance, although it is a proprietary option [29]. All 3 textures and their effects on the 3D model are shown with a white material in *Figure 6*. The textures were compressed with the BC7 codeq in .dds, a

format that minimizes compression losses and that is easy to decompress, so that it is especially suitable for real-time rendering. Although there are other formats or codecs that can reduce file sizes even further, the BC7 real-time decompression time is at present one of the shortest. The reconstruction procedure therefore produced a 3D model, consisting of 35,134 triangles, and a material composed of three 4k textures with low compression rates. For its distribution, the .fbx format was chosen, although other popular options such as .obj. Currently, .fbx is the standard for the integration of 3D models into development engines. In addition, .fbx allows for seamless integration of other metadata, such as animations and textures [32], which is of great importance in a textured 3D model that can also be used as a VA.

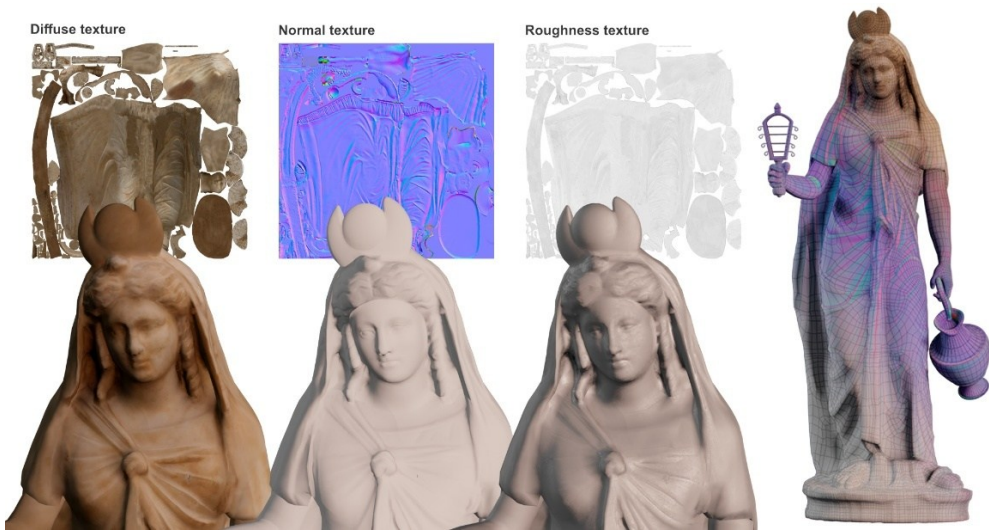


Fig. 6 Images of the 3 textures and their effects on the 3D model: diffuse texture (left); normal texture (center); and roughness texture (right).4.2

4.2 Model assessment

Finally, three analyses were conducted to assess the technical specifications of the model and the procedure: a discrepancy analysis of the reconstructed 3D model (Low-Poly) compared to the photogrammetric model (High-Poly), a detail concentration analysis and a Level of Detail (LoD) analysis. The analyses were carried out with respect to the photogrammetric model. The purpose of the analyses was to verify correct execution of the retopology process that should maintain the shape of the photogrammetry and place the highest number of vertices in the most relevant and expressive areas of the 3D model with a suitable LoD. Since the optimization process involves a trade-off between surface fidelity and compatibility with interactive environments, it is crucial to ensure that this process has been carried out correctly. Otherwise, part of the surface fidelity may have been lost,

something of great importance in CH work [22], without achieving any actual improvement to the 3D model.

The discrepancy analysis was conducted using the software Cloud Compare, a standard open-source tool [53]. The reconstructed parts that could not be compared were excluded from the analysis, since there was no photogrammetric reference. The minimum and the maximum distances between both models were -39.65 mm and 26.63 mm, respectively, with a Mean (M) of 0.4 mm and a Standard Deviation (SD) of 3.7 mm. *Figure 7* displays the heatmap generated from the analysis. Both the lower and the upper thresholds were adjusted from -15 mm to 15 mm, so that the deviations of the model could be seen more clearly. Accordingly, blue represents negative and red represents positive deviations. An enlargement of the upper torso of Isis showing the most pronounced deviations can be seen below in *Figure 7*.

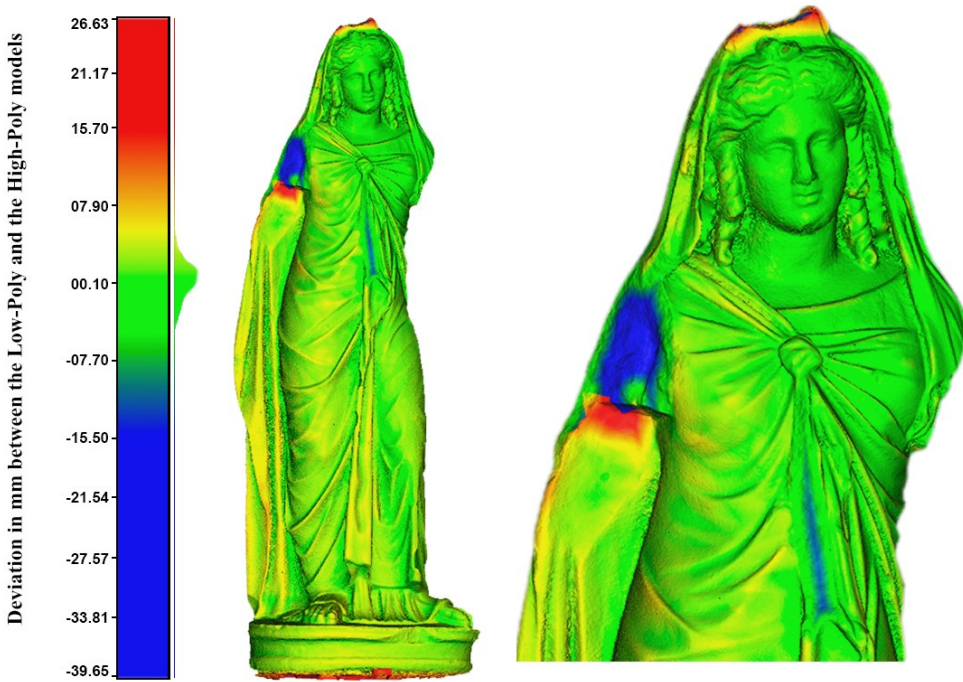


Fig. 7 Results of discrepancy analysis heatmap with enlargement of the upper torso (right)

The results indicated that, on average, the deviation of the model was around 1 mm with a SD of 4 mm. Such a relatively high SD was very likely due to localized maximum deviations, which reached up to 40 mm. Significant deviations that may be attributed to the restored parts of the model, shown in *Figure 7*, where the lower part of the knot of Isis is highlighted in blue. The heatmap of the model, shown in *Figure 7*, represented most of it in green, indicating deviations of at most ± 1 mm. Additionally, all deviations were either concentrated in the reconstructed parts

(crown and lower part of the knot) or near the shoulders, which connected to the newly reconstructed parts. These areas were excluded from the Low-Poly model to enable a more accurate analysis; however, the lack of nearby geometric references eventually led to the appearance of deviations in the results. This occurred because the optimization process was carried out using the fully reconstructed statue, not just the photogrammetric model. The only exception was on the left-hand side of the mantle, due to its more complex shape. It would require further geometry for a completely accurate representation. The analysis demonstrated satisfactory overall results, generally showing deviations around 1 mm in a full-size 1020 mm high model.

For the analysis of detail concentration assessment, both a qualitative and a quantitative analysis were conducted. For the qualitative analysis, the MeasureIt add-on, with which metric measurements can be taken within the Blender environment and other Blender add-ons were used. The latter software was chosen out of convenience, as it is pre-installed with Blender. Various areas were calculated, and the number of their vertices were counted. The segmentation of the statue into its constituent parts was based on semantic and anatomical criteria. The results of the vertex count, area, and average vertex density per cm^2 are shown below, in *Figure 8*, for each part of the model. The vertex concentration of the model is also shown in the same *Figure* using a color-coded heatmap in blue and red where darker tones of red indicate higher concentrations.

These data reveal that the lowest detail concentration is found in the mantle, tunic, arms, and pedestal. Conversely, the highest detail concentration is observable in the head, hands, feet, knot and instrument. Throughout the model development process, efforts were made to prioritize retopology, by enhancing detail in elements of significant iconographic importance or areas with high expressiveness, essential for accurate animation. In that regard, the most important iconic symbols of the goddess, her situla, the sistrum and the Isiac knot, the hair, and her headdress were modeled in detail. Although the tunic and mantle had the lowest vertex concentrations, they were detailed for an accurate depiction of the wet drapery effect, as shown in the vertex distribution in *Figure 8*. In contrast, the face and hands, as expressive features that were crucial to the animation, were highly detailed [14]. Facial details, critical for facial expressions, were specifically concentrated around the mouth, nose, and eyes. The high vertex concentration at the sculpture's feet was because the vertices were at the endpoints of many loops within the 3D model.

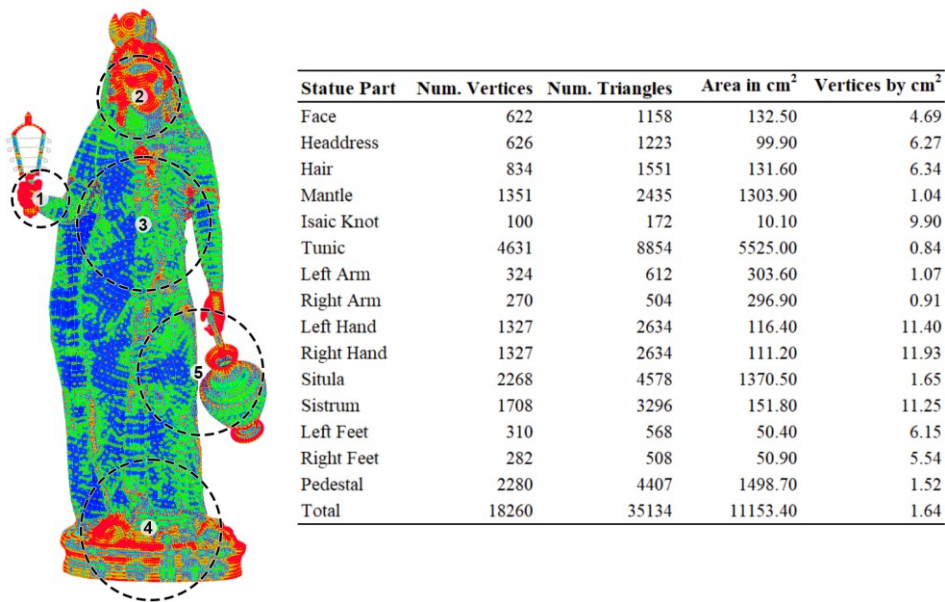


Fig. 8 Results of the detail concentration analysis. Heatmap (left) and table results (right). The clusters within the 3D model, defined based on vertex concentration, are represented over the heatmap. Each cluster is labeled with its corresponding centroid number, and the cluster radius is indicated by a black dashed line

For the quantitative analysis, a clustering of regions within the 3D model was performed using the k-means algorithm. To conduct this analysis, the Euclidian coordinates of each vertex were extracted and subsequently subjected to the clustering process. The entire procedure was carried out using the Hartigan-Wong algorithm, with a varimax rotation of 10 [39]. Initially, clustering was performed using a range of 1 to 10 clusters. The Elbow Method was then applied to evaluate the Within-Cluster Sum of Squares, revealing that the most significant drop occurred at five clusters. Beyond this point, the improvement from adding more clusters became marginal, indicating that 5 is the optimal number of clusters. Subsequently, spheres were modeled around each cluster using their centroids as centers in order to determine the spatial area occupied by the clusters within the 3D model. The standard deviation of each cluster was calculated to define a representative radius, indicating its spatial extent in the 3D environment. Specifically, the square root of the Within-Cluster Sum of Squares was divided by the number of points in the cluster. The resulting value reflects the average dispersion of points around each cluster centroid. *Figure 8* shows the identified clusters, outlined with dashed black lines over the 3D model's heat map. Each cluster is labeled with its corresponding centroid number. All relevant data regarding the clusters and their generation are provided in *Annex II*. As illustrated in *Figure 8*, the results of the quantitative

analysis support the findings of the qualitative assessment. The areas highlighted by the clusters correspond to the hands and instruments, head, feet, and the central region of the model near the knot. These regions are also the most visually prominent on the heat map. Moreover, the segmentation of the model based on semantic criteria, also visible in *Figure 8*, shows that these areas contain the highest concentration of vertices. This confirms that these regions of the 3D model are the most relevant in terms of detail, as well as the most expressive areas, where the key attributes of the deity are also located.

For the LoD analysis, LoDCalculator, an add-on for Blender designed to evaluate LoD, particularly in 3D models of CH [77] was used. This software provides a score of 1 out of 5, with half-point increments. The model received a score of 4 out of 5, indicating a high LoD. However, this score is primarily due to the "low" resolution of textures applied to the goddess's instruments. Since these objects did not have a primary reference based on photogrammetry [63], priority was given to displaying the rest of the sculpture to occupy a larger area in the UV space, resulting in a relatively lower resolution for the instruments [34]. Excluding the instruments from the analysis, the LoD score reaches 5 out of 5. Nevertheless, a score of 4 out of 5 still indicates a high LoD [77]. These results are indicative, but in any case, they suggest that the generated 3D model has a high LoD.

5. Development of the iVR experience

An iVR experience was designed to test the 3D model. Created in collaboration with the Museum of Burgos (Spain), it was tested with the museum's visitors during an annual 'White Night' cultural event, during which the city museums remain open during the event and receive large numbers of visitors.

The aim was to test the quality of the model in an iVR experience, so it was necessary to create a 6 Degrees of Freedom (6DoF) iVR experience, so that users could freely look at and move around the virtual environment [78]. The experience followed a simple design process, due to the limitations of the evaluation context. As noted in various reviews, iVR experiences within museums are often more limited than in other contexts, because they are usually tested with very large and diverse groups [10]. The large number of people testing the experience, and the diversity of profiles complicate the execution of complex experiences and evaluations, as situational control is reduced [76]. This aspect has been particularly important in this experience, as the 'White Night' is an event that attracts a particularly large number of visitors. In other contexts, less constrained experiences could be considered.

The iVR experience was of the Explorative type, meaning that users could not directly interact with the environment and their range of movement was limited [17]. A Real Walink-type interaction system [7], also referred to as Room Scale in other reviews [76], was used in which the user can only interact within the environment by walking around it. The movement area of the experience is approximately 2m2. Rather than other more complex systems, its use removes the need to include controllers or hand-tracking systems and simplifies the iVR experience, making it more accessible to all kinds of participants. In this iVR experience, users can view the photogrammetric sculpture of Isis and its reconstructed version for a total of 2 minutes (1 minute per version); information that is communicated to the users through a visual message before the experience begins. The user appears in front of the photogrammetry sculpture, displayed at real size, and can move around it for close examination. Due to the high PC of the photogrammetric version of the model (5,415,819 triangles), a decimated version with a PC of 24,406 triangles was generated. One minute later, the photogrammetric version of Isis is replaced by the reconstructed version of Isis. So that the change is clearer for the user, the virtual environment also changes: while the users are observing the photogrammetric version, they are in a museum; when they see the reconstructed version, they find themselves within a Roman temple dedicated to the goddess. No specific heritage site is reconstructed in the temple environment. These genetic scenarios were obtained from the Unreal Engine Marketplace, now known as Fab. *Figure 9* shows an image of the iVR experience depicting both scenarios and reconstructions of Isis. A background ambient soundtrack remains on throughout the experience.

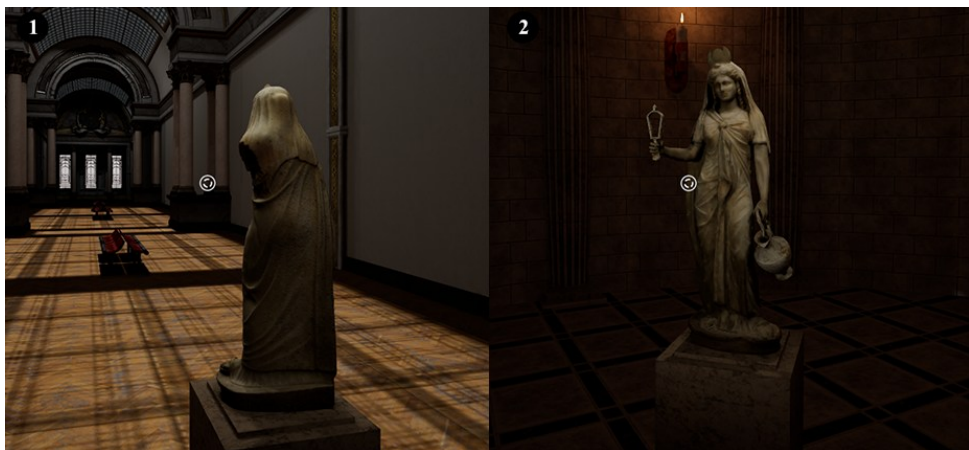


Fig. 9 Screenshots of the iVR experience: 1) the original Isis and 2) the reconstructed Isis

The experience was developed for standalone HMDs (Oculus Meta Quest 2 and 3) using Unreal Engine 5. It was the chosen type of HMD, because it requires no

computer to function [5], facilitating both its transport and installation in a museum. Additionally, Unreal Engine was selected for its capability to generate photorealistic environments [10], due to the research team's prior experience with this engine and its ease of use [58].

6. Evaluation

The main characteristics of the evaluation will first be described, followed by the results and discussion.

6.1 Materials and Methods

The evaluation procedure consisted of a single questionnaire administered at the end of the experience. Although administering questionnaires both before and after the iVR experience can be useful to obtain more robust results [76], only one questionnaire was administered to simplify the evaluation method. A more complex evaluation method with multiple tests could in a context of limited control over the users have led to errors [89].

The questionnaire was derived from the Questionnaire sur l'État de Présence [92], a 2005 revision of the Presence Questionnaire (PQ) proposed by Witmer B.G. and Singer M.J. [91]. The aforementioned questionnaire was chosen, as it is recognized as a standard for the evaluation of various factors related to iVR experiences [50].

The PQ was slightly modified to meet the specific needs of the experience. Firstly, its original 7-point Likert scale was adjusted to a 5-point scale for the purpose of simplification. A change that was due to the challenges of conducting an evaluation in a musealization context. Secondly, due to the limitations of the experience in terms of complexity, all questions directly related to interaction or controls were removed, including all questions on the Interface Quality factor, which refer to the quality of the interface and control [91]. Finally, two new blocks of questions were added. The first block contained demographic questions such as age, gender, and previous experiences with iVR. The second block consisted of questions specific to the experience, focusing on the realism of the 3D model and the quality of the reconstruction; regarding these questions, participants were informed that the environments in which the statue was placed were generic, and that the questions specifically referred to the figure of the goddess Isis. In addition, a question about cyber sickness symptoms, a very important factor for the assessment of iVR experiences, was also added [7]. *Table 1* lists the questions. Considering the above adjustments, the factors evaluated in the final questionnaire were as follows:

- *Cybersickness*: a condition marked by symptoms such as nausea, and headaches experienced by users in virtual reality (VR) environments, which have primarily been explained through sensory conflict theory [19]. The cybersickness factor was evaluated with 1 question.
- *Involvement*: a psychological state that arises from directing mental energy and attention toward a coherent set of stimuli or activities. It is enhanced by tasks and activities that cognitively, physically, and emotionally stimulate, challenge, and engage an individual [92]. The involvement factor was evaluated through 9 questions.
- *Adaption/Immersion*: terms used to describe the degree of the user's perceived competence at navigating the virtual environment and how quickly they can adjust to the iVR experience [91]. The adaption/immersion factor was evaluated with 5 questions.
- *Visual Fidelity*: used to evaluate the ease of viewing using vision throughout the iVR experience when conducting active searching, surveying, or examining objects [91]. The visual fidelity factor was evaluated with 2 questions.
- *Reconstruction questions*: used to evaluate specific aspects of the restoration work in this project. The reconstruction evaluation factor was evaluated with 3 questions.

Table 1. List of questions used in the questionnaire

N	Factor	Item
1	Demographic	Sex
2	Demographic	Age
3	Demographic	Have you ever used a Virtual Reality headset before?
4	Cybersickness	Did you feel dizzy during the experience?
5	Involvement	How much were you able to control events?
6	Involvement	How responsive was the environment to actions that you initiated?
7	Involvement	How natural did your interactions with the environment appear?
8	Involvement	How much did the visual aspects of the environment involve you?
9	Involvement	How natural was the mechanism which controlled your movement through the environment?
10	Involvement	How compelling was your sense of objects moving through space?
11	Involvement	How much did your experiences within the virtual environment appear to be consistent with your real-world experiences?
12	Involvement	How involved were you in the virtual environment experience?
13	Adaptation/Immersion	Were you able to anticipate what would happen next in response to the actions that you performed?
14	Adaptation/Immersion	How completely were you able to actively survey or search the environment using vision?
15	Adaptation/Immersion	How much delay did you experience between your actions and the expected outcomes?
16	Adaptation/Immersion	How quickly did you adjust to the virtual environment experience?
17	Adaptation/Immersion	How proficient in moving and interacting with the virtual environment did you feel at the end of the experience
18	Visual Fidelity	How well could you examine objects from multiple viewpoints?
19	Visual Fidelity	How closely were you able to examine objects?
20	Reconstruction questions	How realistic did you find the sculpture of Isis?
21	Reconstruction questions	Do you think the 3D model you have seen faithfully reproduces the appearance of Isis?
22	Reconstruction questions	Were you able to differentiate the reconstructed parts from the original parts of the sculpture?

6.2 Results and discussion

Firstly, the demographic results are detailed. Secondly, the results of the factors that were analyzed are explained and discussed. Finally, the results of a clustering analysis on user behavior are presented.

The 60 individuals of the evaluation sample had a mean age of 47 years old with an SD of 17 years. There were 33 (55%) women and 27 (45%) men, 43% of whom had previous experience with iVR. *Figure 10* shows a group of users viewing the experience during the ‘White Night’ event. The data were processed by calculating M and SD. The results of Question 15 were reversed, with maximum and minimum values inverted, as it was the only question posed in reverse order. All the data can be consulted in *Annex II. Table 2* presents the sample results for each factor, showing M and SD. Considering that the musealization experience is designed for a diverse range of users, the results were categorized based on the demographic profiles of the users, to assess their impact on each factor. The results were divided into groups based on their prior iVR experience and age, splitting the sample into four equal quartiles of 15 individuals with the following characteristics: Age Group 1 (10-34 years old), Age Group 2 (34-53 years old), Age Group 3 (54-60 years old), and Age Group 4 (60-75 years old). In that way, age-related differences could be identified in view of the wide age range of the sample.



Fig. 10 Group of users testing the experience during ‘White Night’ event

Overall, the results of the study were highly satisfactory, with Visual Fidelity, at 3.73, being the only factor scoring below 4 out 5. There were minimal differences between the other groups, with Age Group 3 standing out for having a slightly

higher score, except in Cybersickness. These results can be contrasted with the results of other studies, in which iVR experiences were evaluated in museum contexts with large samples and wide age ranges. The way that the results were affected by age, due to factors such as the younger populations' experience with new technologies [68], interest in new technologies [54], and perception of CH [75] can be highlighted in this research. In addition, these results could also have been affected by the novelty effect, i.e, the excitement that any new technology causes in new users, enhancing their attention during initial interactions [59]. An effect that was also evaluated in other iVR studies, revealing significant differences among users with varying levels of experience with this technology [59]. These results with few variations between users of different ages and previous iVR trials may be attributed to the simplicity of our iVR experience. Positive results were expected in terms of usability and satisfaction across all age groups, regardless of prior experience with iVR, as the iVR experience was designed to be simple and accessible to all types of audiences. It also reduced age-related differences such as the novelty effect.

Table 2. User results in relation to the different factors, showing both the M and the SD of each factor

	N	Cybersickness (M/SD)	Involvement (M/SD)	Adaption/Immersion (M/SD)	Visual Fidelity (M/SD)	Reconstruction questions (M/SD)
Total	60	4.58 / 0.94	4.06 / 0.86	3.73 / 1.06	4.05 / 0.93	4.02 / 0.92
No iVR Experience	34	4.56 / 1.05	4.10 / 0.86	3.67 / 1.06	4.01 / 0.94	4.07 / 0.96
Previous iVR Experience	26	4.62 / 0.80	4.00 / 0.87	3.81 / 1.05	4.11 / 0.92	3.94 / 0.85
Group Age 1	15	4.80 / 0.56	3.91 / 1.00	4.02 / 1.05	4.46 / 0.81	3.78 / 1.06
Group Age 2	15	4.20 / 1.42	3.96 / 0.90	3.51 / 1.05	3.71 / 1.01	4.07 / 0.78
Group Age 3	15	4.60 / 0.91	4.23 / 0.72	3.84 / 1.09	4.13 / 0.73	4.13 / 0.89
Group Age 4	15	4.73 / 0.59	4.15 / 0.78	3.56 / 0.99	3.93 / 1.02	4.05 / 0.93

Delving deeper into the differences between the various user-types, a user behavior analysis based on k-means clustering, in which users are grouped into clusters based on response patterns, was also conducted [41]. For the analysis, Questions 1 to 3 were excluded, as they pertained to demographic aspects that would have influenced the composition of the clusters. The remaining questions were analyzed using the Hartigan-Wong algorithm [39].

Figure 11 depicts the Cluster plot on the left-hand side, illustrating the two clearly independent clusters, Cluster 1 (in blue) and Cluster 2 (in green). Both the X and the Y-axis represent the weight of the two dimensions identified for clustering. On the right-hand side, a box plot shows the scores of both clusters for each factor. The Y-axis displays the distribution of the scores, while the X-axis shows each factor divided between the two clusters, with Cluster 1 always on the left and Cluster 2 on the right. Examining the demographic data, Cluster 1 has an average age of 27, with

59% of its members having prior experience in iVR. In contrast, Cluster 2 has an average age of 53, with 41% of its members having prior experience in iVR. The older users of Cluster 2 might therefore have tried out iVR on fewer occasions than the younger members of Cluster 1.

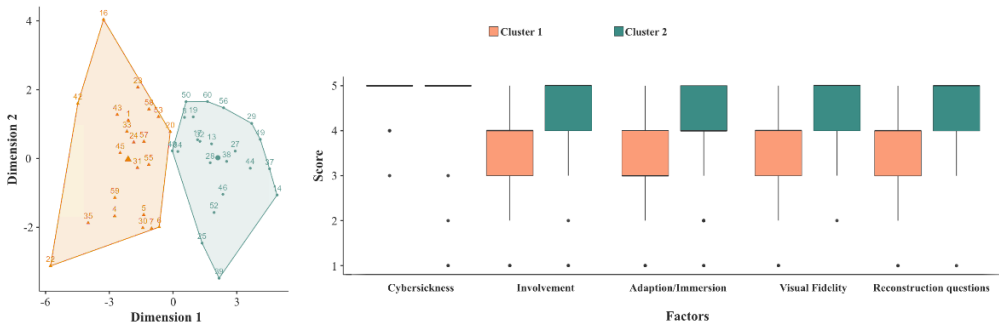


Fig. 11 Cluster Plot (left), box plot with the scores of the two clusters in each factor (right)

As observed, Cluster 1 groups together lower scores across all factors, concentrated around 3 or 4. In contrast, the scores for Cluster 2 (older age group and less experienced in iVR) are concentrated around 4 to 5. The exception is the Cybersickness factor, where both groups have the same score, concentrated around 5. The positive results of both groups were also echoed in previous studies, in which the impact of the novelty effect and age on user behavior was higher among older and less experienced users [59, 68].

The results of this study indicate a very positive response from the sample across all the factors that were evaluated, demonstrating high usability and user satisfaction with both the iVR experience and the reconstructed 3D model. Although no obvious differences were observed between age groups and prior iVR experiences, those differences could be detected using clustering methods, which revealed typical behaviors of such users in similar experiences, with higher results among users with less prior experience in iVR. The lack of clear differences at first glance may be indicative of a well-designed iVR experience for a variety of audiences within musealization contexts. The simple design was intended to mitigate the friction that this technology can cause in uncontrolled environments with diverse user profiles, such as museum exhibitions [10]. The results were highly satisfactory in that regard, although the 3D model has still to be implemented in more complex iVR experiences, so that its potential as a VA may be further explored.

7. Conclusions

The development, assessment, and iVR implementation of a virtual reconstruction of the sculpture of the Isis of Clunia (Spain) from the 2nd c. AD has been presented in this study. The reconstruction procedure of the 3D model utilized close-range photogrammetry to build an initial model. Subsequently, the photogrammetric model was supplemented with historical information through 3D modeling for non-structural restorations and digital sculpting for structural restorations. The model was then optimized through retopology and texture baking. The deviation of the 3D model from the original photogrammetry was few mm and its detail were concentrated in the iconic attributes of the sculpture and the movable, expressive parts, facilitating its animation and its use as a VA with a high LoD. This process resulted in a light 3D model ready for implementation in iVR experiences and with the potential to be used as a VA. In addition, the model is open access and freely downloadable. The procedure executed in this research has yielded satisfactory results. However, a limitation of this procedure is the loss of fidelity of the generated model in relation to original statue, due to the data acquisition and optimization methods employed.

An explorative iVR experience has been developed to test an initial implementation of the model. Users were able to observe the sculpture in its two states: original and reconstructed. The results of the iVR experience were tested with a sample of 60 people during the 'White Night' event at the Museum of Burgos (Spain). The 3D model was well received, and the evaluation yielded very positive results in terms of usability and user satisfaction, for both the 3D model and the iVR experience. Further analysis of the results with clustering methods showed less satisfactory results between young people with previous iVR experience and higher satisfaction among older people who had never experienced iVR before, due in all likelihood to the novelty effect [59]. In any case, the effect was hardly noticeable in the results of both groups, which were very satisfactory. In the future, it is planned to use the model in more complex iVR experiences and to explore its potential as a VA, in addition to assessing the degree of user interaction with users from a wide range of demographics in this more complex experience. Moreover, the development of simpler iVR experiences focused on the Isis of Clunia is also planned as part of the activities of the Museum of Burgos.

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Supplementary materials. The following supporting documentation can be downloaded at: https://github.com/DigiUBU/Isis_3DModel

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This publication focuses on optimizing the design of iVR experiences for users of different age profiles and addresses the evaluation of iVR experiences, building on the outcomes of *Result 1* and the pilot validation of *Result 3*: 1) the challenges in implementing interactivity in 6DoF iVR experiences, particularly for broad and diverse audiences; and 2) the difficulties of conducting robust iVR evaluations in public contexts. For this study, the statue of Isis from Clunia was selected as a case study, implementing the 3D model developed in *Result 3* within a dissemination iVR experience with different levels of interaction evaluated at the Museum of Burgos by a sample of 171 users from different age groups.

The outcomes of this research complement the previous results by implementing earlier findings in an iVR experience that addresses the optimization of the three phases of creating an iVR experience for CH dissemination: Preparation, Execution, and Post-processing. The evaluation provided solid insights into the specific needs of each group in designing iVR experiences highlighting: 1) children’s preference for interactivity; 2) young adults’ adaptability; and 3) older adults’ preference for immersion. This result is aligned with Goals 3 and 4. *Table 6* presents the bibliometric data of this publication.

Table 6. *Bibliometric data of Result 4*

TITLE	Age matters: Adapting Immersive Virtual Reality Experience to different age profiles
STATE OF PUBLICATION	Peer review (Manuscript submitted on 18/09/2025)
JOURNAL	Virtual Reality
DATE	2025
JCR	Q1 Computer Science, Software Engineering (2023 release)
DOI	Not applicable
AUTHORS	Bruno Rodriguez-Garcia, Ines Miguel-Alonso, David Checa, Andres Bustillo
KEYWORDS	Virtual Reality, Human Computer Interaction, User Experience, Children, Age, User Centered Design

AGE MATTERS: ADAPTING IMMERSIVE VIRTUAL REALITY EXPERIENCE TO DIFFERENT AGE PROFILES

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Abstract. Immersive Virtual Reality (iVR) has reached a level of technological maturity that enables its use for the general public. However, further investigation is needed into the optimization of iVR applications and particularly, their design features in relation to various user characteristics such as age and previous iVR experience. To solve this issue, this study evaluates a Cultural Heritage dissemination experience in iVR, tested in a real-world setting, the Museum of Burgos (Spain), with participants from three age groups: children, young adults, and older adults. The iVR experience was structured in four levels of progressively complex interaction. A control group was formed to view a video containing the same dissemination content. A total of 171 participants completed a three-steps assessment measuring prior knowledge, User Experience (UX), and learning outcomes. The findings emphasized that iVR's strengths, immersion and interactivity, must be strategically optimized to outperform more well-established dissemination formats like video. The results showed that children responded positively to high interactivity; their motivation and rapid adaptation supported the use of interactive formats, provided cognitive demands are gradually introduced. Young adults exhibited the highest adaptability and fastest completion times, performing well across all interaction types, though with moderate UX ratings. Older adults preferred soft interaction and immersive aesthetics, achieving better learning outcomes in this context but extending the time to complete the iVR experience.

1. Introduction

One of the main barriers to the adoption of new technologies is the level of difficulty that users face in adapting to them [1]. Successful implementation requires attention to usability and interface design [2], as personalized approaches such as User-Centered Design (UCD) [3], and affordability [4]. Without fulfilling those conditions, new technologies often remain limited to early adopters and research prototypes, complicating their real-world integration [5]. Even when the advantages are clear, implementation can still be obstructed by low levels of user acceptance and contextual barriers [6].

The release of Oculus Rift, an affordable Head-Mounted Display (HMD), was a significant milestone in the broader adoption of immersive Virtual Reality (iVR). iVR is primarily characterized by its interactivity, allowing users to alter and engage with the virtual environment at deeper levels, and by its capacity to induce a strong sense of presence or immersion, often described as the feeling of "*being there*" [7]. The real-

time interaction provides benefits such as operating hazardous machinery without risk [8]. Likewise, the sense of presence enables users to explore past events [9] or long-lost historical environments from a first-person perspective [10].

Despite the great presence of iVR in literature [11], [12], its limitations, particularly interaction paradigms, continue to hinder adoption [13]. Many issues arise not from hardware but from design shortcomings, which could be improved adapting iVR to different user characteristics, such as prior experience [14] or age [15]. Typically, User Experience (UX) in iVR has been studied primarily in young adult populations [16], often neglecting other user groups in which iVR has demonstrated notable benefits, such as improving physical conditions in older adults [17] or enhancing motivation of children in settings like museums [18]. While other studies have addressed these populations, such research remains relatively scarce [19]. Many studies involving older adults focus on users with dementia or other impairments [20], so their results are inapplicable to populations in good health [21]. Additionally, sample sizes tend to be limited, often involving only around 20 participants per group [22]. Moreover, these studies typically compare only two age groups, one of which is almost always young adults, the most studied group in iVR research [16], paired either with children [15] or with older adults [23]. Although such investigations yield valuable insights, they rarely compare multiple age groups simultaneously within the same experience, which would provide more comprehensive conclusions regarding UCD. Lastly, these studies generally focus exclusively on iVR experiences, with few comparisons to more established technologies such as video.

This study addresses the gap in user-adaptive iVR design, focusing on museums as a real-world context. This context was selected because it implies usually diverse background audiences [24], different age groups [18] and often with low prior iVR experience [25]. The high visitor numbers and limited time make museum-based iVR particularly challenging to implement [26]. To study the optimization of the user-adaptive iVR design, this study presents an iVR experience specifically designed to evaluate UX, with four levels of increasing interactivity, and extract UCD guidelines for iVR experiences design. Its validation has been done on a large sample ($N=171$), that covers different age groups (children, young adults and elderly). The experimental design incorporates a wide range of variables that have been considered relevant in other studies related to UX in iVR: prior iVR experience [14], level of interaction (Kim et al., 2020), locomotion systems [28], and learning outcomes [29]. For this purpose, an iVR experience was created around the Isis of Clunia, a Roman sculpture from the Museum of Burgos (Spain) discovered in Clunia Sulpicia, one of the most important roman cities in the north of the Iberian Peninsula. This sculpture has been previously reconstructed and validated as a

Virtual Agent (VA). The iVR experience was used to disseminate knowledge about Cultural Heritage (CH): Isis's origins, Roman iconography, and the specific artistic features of the sculpture. Finally, a control group watched a video with the same content, one of the most established technologies for educational dissemination in museum contexts [30] to compare learning outcomes.

The structure of this research is as follows. *Section 2* summarizes the most relevant features of the case study, the Isis of Clunia. *Section 3* provides a detailed description of the design and development of the iVR experience and the video. *Section 4* outlines the evaluation procedure followed in this research. *Section 5* explains and discusses the study's results, offering a set of best practices. Finally, *Section 6* provides a summary of the main conclusions and future lines of this research.

2. Study Case: Isis of Clunia

The historical content about the goddess Isis, and specifically the Clunia sculpture, is broad and complex. This section summarizes the main components evaluated in both the iVR experience and the video: 1) Origins and cult, 2) Iconography, and 3) Formal characteristics of the Clunia sculpture.

Isis, an Egyptian goddess of fertility, motherhood, and magic, was the wife of Osiris and the mother of Horus. After Osiris's murder, she restored his life with her magic [31]. Her cult endured Roman assimilation of the Egyptian pantheon and was adopted in Hispania, where it became linked to motherhood [32]. The Clunia sculpture, like others in Roman culture, reflects a Hellenistic rather than Egyptian style [33]. It included four attributes [32]: 1) the sistrum, an ancient rattle made of metal rods, usually held in her right hand, 2) the situla, a ritual pitcher typically carried in her left hand, 3) the crescent moon crown adorning her hair, and 4) the Isiac knot, which gathered her mantle around her chest. *Figure 1.2* shows the virtual reconstruction of the sculpture highlighting the above attributes.

The sculpture that dates to the 2nd century AD, was discovered in 1853 by Salomón Remigio. Its deterioration over the centuries had left it without arms and most of the other attributes, except for the Isiac knot [34]. Its original location is thought to have been Clunia's theater [35], shown in *Figure 1.3*. Clunia Sulpicia was one of the most important Roman cities in the north of the Iberian Peninsula, in the present-day Burgos province. The city is known for its forum, baths, and theater. Today the sculpture is exhibited at the Museum of Burgos (*Figure 1.1*), being one of the museum's key pieces.



Fig. 1 1) Image of the Isis sculpture at its current location in the Museum of Burgos, 2) Virtual reconstruction of the statue with each main attribute highlighted, and 3) Image of the Roman theater of Clunia, where the sculpture was discovered

3. Materials

First, the design and development of the iVR experience will be described, followed by a description of the video made for the control group. Both the iVR experience and the video may be viewed in *Annex I*.

3.1 Design of the iVR experience

The design of the iVR experience and an overview of its levels are outlined below, after which its development and format-related aspects are addressed.

3.1.1 iVR design

The iVR experience is designed to convey the historical content from *Section 2* to a broad museum audience. It aims to be accessible and enjoyable for children, young adults, and elderly users, as well as for those with low prior experience with iVR. The goal is to combine education with engagement, balancing enjoyment and content understanding. The following paragraphs describe the main design challenges addressed during its development: the research approach, the time, the user motivation, the novelty effect, the knowledge transmission and the adverse effects of iVR.

The research approach was aimed at identifying the most suitable design patterns for different user profiles, which is a limitation compared to commercial products that rely on established patterns. To do so, progressively complex interactions were implemented in a level-based structure. This structure splits the iVR experience into two halves. One of soft interaction with Levels 1 and 2, and a more complex hard interaction with Levels 3 and 4. Each level records completion time and a behavioral indicator related to the main interaction, detailed in the following subsections. The design enhances the research potential in so far as users are exposed to a range of interactions within the iVR environment, facilitating behavioral measurements across scenarios.

The time users can spend in an iVR experience is a critical design factor that can vary depending on many other variables. Experimental evaluations of prolonged iVR experiences also pose significant challenges [36]. The iVR experience was therefore designed to last approximately 6–7 minutes, which was considered an appropriate length of time for the context, even though slower users may need extra time.

User motivation is crucial for sustaining engagement during iVR experiences [37]. It can be enhanced through the use of narrative elements [17]. In the iVR experience, the goddess Isis appears at the Roman Theatre of Clunia as a VA who asks users to help reconstruct her sculpture by selecting between various options. VAs have been explored in previous research to boost engagement, especially among children [38]. Likewise, visual and auditory elements, including the goddess' voice, support historical learning and have proven satisfying for elderly users [39]. The content is embedded within a coherent narrative, interweaving information on her origins, worship, and formal characteristics rather than presenting a linear account.

The novelty effect is the initial excitement of using new technology and can influence learning and motivation [40]. It is of particular relevance to museum audiences whose prior iVR experience is often limited [41]. The level-based game structure was implemented to reduce the impact of the novelty effect, so that users gradually acclimate as the level of intensity increases. Although tutorials can mitigate the novelty effect [42], they were excluded to avoid lengthening the iVR experience and to study user interaction in a real-world context for deriving adaptive design guidelines.

Knowledge transmission is a widely studied component of iVR experiences, often guided by such theories as the Cognitive Theory of Multimedia Learning [43] or gamification [44]. Applying these theories to iVR experiences for a broad audience is challenging, as the iVR experience cannot only be focused on learning. Even so, storytelling, which is considered a form of gamification, was employed to enhance engagement [45]. The design leverages iVR immersive characteristics to convey knowledge, using the Roman Theatre of Clunia as a visual setting and spatialized audio for the differentiation of auditory cues. Interaction allows users to pick up and explore key visual elements, as the statue or an old drawing of it.

Adverse effects of iVR are an important consideration when designing for a varied audience, particularly comfort and cybersickness [46]. Usually designed for young adults, HMDs can cause fit and usability issues for children [47] and elderly users [22]. In addition, misalignment may lead to vision problems among childrens [4], though newer HMDs have since reduced that risk [48]. To solve this issue, modern HMDs with improved weight distribution and alternative straps were used to enhance ergonomics [49]. Moreover, controllers were used because they generally provide better usability than other solutions such as hand tracking [20]. To further enhance usability, the interaction was designed to be operable with a single hand [17]. Active movement was employed to further reduce discomfort and cybersickness, especially for elderly users, with only one level using an alternative locomotion system. Finally, the short duration of the iVR experience lowers the risk of adverse effects.

Summarizing, the iVR experience was designed to balance key factors without over-targeting a specific audience. The museum setting constraints were considered to create an enjoyable iVR experience for most users while conveying the sculpture's history and iconography. In *Figure 2* each level of the iVR experience is presented, while vertically, the most relevant characteristics of the levels are described.

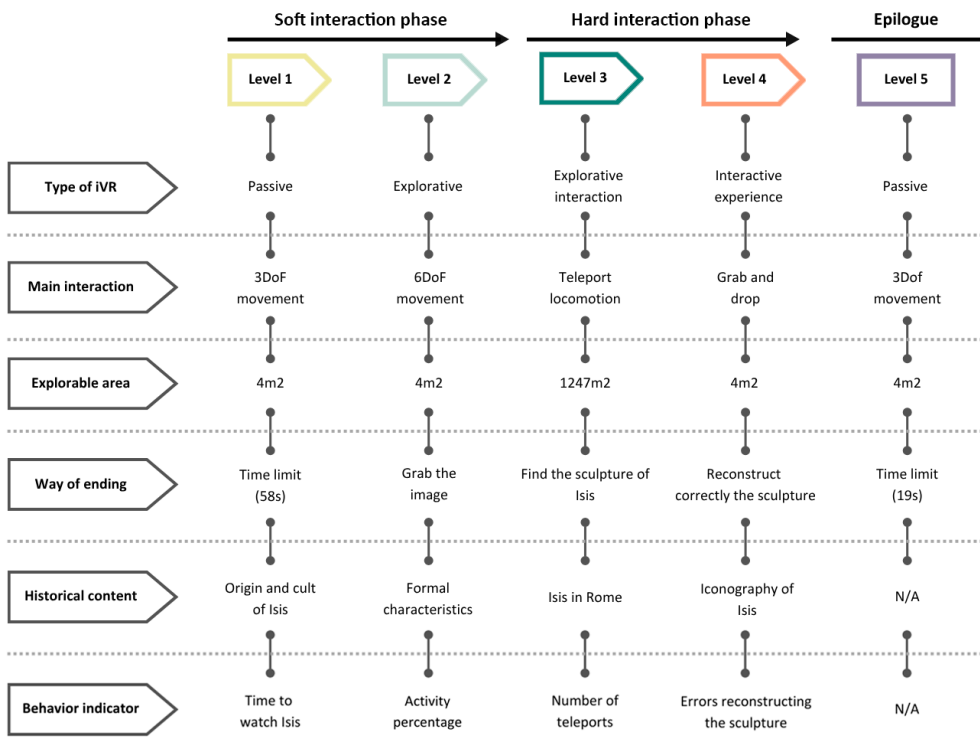


Fig. 2 Summary of the most relevant characteristics of the iVR experience levels. Levels are shown horizontally, while their characteristics are displayed vertically

3.1.2 Level 1 design

This level takes place in a generic Egyptian temple with dim lighting and the sound of fire. At the center stands the fully reconstructed statue of the Goddess Isis, as shown in *Figure 3.1*. After 5 seconds, the statue begins to speak, providing the user with context about the goddess’s origins as well as the task to be completed in the experience: to locate and to reconstruct her statue in the theater of Clunia.

This level introduces the goddess’s Egyptian origins and the narrative goal of finding and reconstructing her statue. From a usability point of view, it is a simple Passive iVR experience, with no direct interaction and very limited movement, though still offering a 6 Degrees of Freedom (DoF) experience. Users start facing the statue’s side and must turn 90°, guided by Isis’s spatialized voice. *Figure 3.2* shows a top-down view of the level layout. The aim of the level is to acclimate them through a basic spatial interaction like a 3 Degrees of Freedom (3DoF) experience. This level ends automatically after 58 seconds without requiring any user action. The behavior indicator is the time users take to look at Isis, showing their reaction to the auditory cue and awareness of turning. The total completion time is also recorded, although it is identical for all users.



Fig. 3 1) User's point of view looking at Isis in Level 1 and 2) Top-down view of Level 1 indicating the initial position of the user, Isis, and the distance between them

3.1.3 Level 2 design

Level 2 takes place at the center of the Roman theater of Clunia with ambient nature sounds, as shown in *Figure 4.1* from the user's point of view. The goddess speaks in a reverberated, undefined voice, explaining the location and task. To proceed, users must move around the stage to grab an image that reveals the statue's current appearance.

The narrative explains the sculpture's formal traits and its discovery, reinforced by Isis's voice, the theater setting, and the image. It advances the narrative by requiring users to first locate the reference image before finding the statue. From a usability perspective, this level introduces 6DoF interaction or Real-Walking [50] in an Explorative experience, where the user can explore the environment but with limited interaction. Unlike the previous level, where darkness and lack of guidance discourage movement, Level 2 motivates users to move around and to interact while searching for the image. The grabbing interaction is introduced at the end of the level and is therefore not strictly part of it. The end of the level is also the end of the soft interaction phase of the iVR experience, with 3DoF and 6DoF movement interactions, while the following levels introduce more complex mechanics in a hard interaction phase.

To complete the level, users must locate and grab the image placed 1.1 m away among low stones, requiring them to crouch. Additional physics-enabled stones surround it, moving when touched. The interaction occurs within a 4 m² area, adaptable to different installation spaces. *Figure 4.2* shows a top-down view of the level layout. As the main interaction is 6DoF movement, the performance indicator is the percentage of time users remain active (over 10 cm/s). The level ends once the image is grabbed, with no fixed duration.



Fig. 4 1) User's point of view looking at Isis in Level 1 and 2) Top-down view of Level 1 indicating the initial position of the user, Isis, and the distance between them

3.1.4 Level 3 design

This level continues in the Roman theatre of Clunia, right after the user retrieves the image. Isis instructs the user to teleport in the search for her statue, marking the end of the level. She also recounts her story.

The goddess's origins and her worship in Roman society are entirely conveyed through Isis's narration during this level. Narratively, it brings the user closer to the main task of finding her statue. In terms of usability, interaction during the level increases by combining the previously introduced grabbing mechanic with a new locomotion system: teleportation, activated by pressing a controller button. The teleportation system, the most common system in iVR experiences [51], turns the level into an Explorative interaction experience where the user can both explore and interact with the environment. To maintain boundaries, teleportation is limited to the stage and seating area of the theater, covering about 1,250 m². *Figure 5.2* shows a top-down view of the level with the designated movement area.

To finish the level, the user must approach the statue, with a spatialized audio cue triggered at 2m distance. *Figure 5.1* shows the user's viewpoint close to the statue, teleporting towards it. The statue lies about 16.5m from the starting point, hidden behind a large rock visible earlier but then concealed, so as not to make the task obvious. Behavior is measured by the number of teleports used and the completion time. The level has no fixed duration, as it depends on the user searching for the statue.

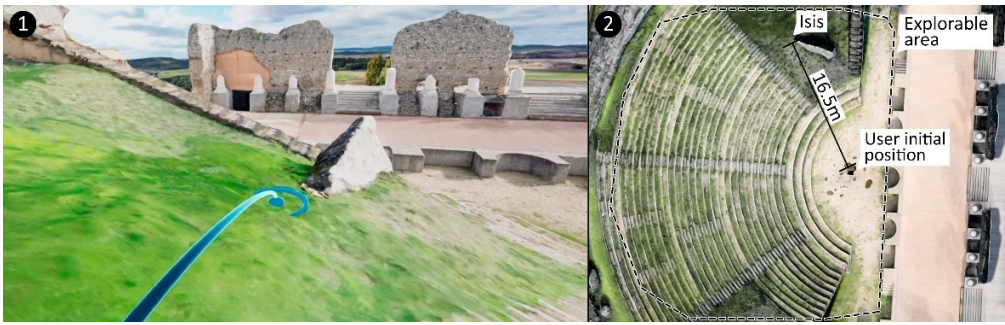


Fig. 5 1) User's point of view near the Isis sculpture in Level 3 and 2) Top-down view of Level 3 showing the user's initial position, the location of Isis, the distance between them, and the size of the explorable area

3.1.5 Level 4 design

At the start of Level 4, the user is teleported to the center of the theater. The Isis statue stands in front of the user, with a table on the left displaying elements and reference images for reconstruction (*Figure 6.1*). Isis explains that the user must rebuild the statue using the correct parts, some of which are distractors, to complete the level.

This level explains the goddess' iconography using the reference images showing her common attributes. Interactivity is integrated into learning, as users examine images and place attributes correctly. Each correct placement prompts Isis to give the object's name and function. The level ends the narrative, with the statue fully reconstructed. In terms of usability, exploration is limited to a 4 m² area with no teleportation, but interaction is maximized, making this level an Interactive experience, where the user has a high degree of interaction but limited exploration.

The level is completed when the user places five items on the statue, of which two are incorrect. The statue, table, and objects are 1 m in front of the user, *Figure 6.2* shows a top-down view of the level layout. Behavior is measured by the number of reconstruction errors and completion time. The duration of the level depends on how long users take to finish, so it is not fixed.



Fig. 6 1) User's point of view at the beginning of Level 4 and 2) Top-down view of Level 4 indicating the initial position of the user, the location of Isis and the table with the objects, and the size of the explorable area

3.1.6 Level 5 design

This level serves as an epilogue that concludes the narrative. The user returns to the same setting as in Level 1, but this time spawns facing the goddess. The statue says goodbye and informs them that it is currently located in the Museum of Burgos. Level 5 lasts 19 seconds, no data are collected, nor is the level included in any subsequent analysis.

3.2 Development of the iVR experience

The iVR experience was developed for standalone HMDs using Unreal Engine 5. The use of standalone HMDs simplifies public use by eliminating cables and external computers. A Windows PC version was also exported for versatility. Unreal Engine was chosen for the team's familiarity, ease of programming, and ability to create photorealistic environments [52], which is an important factor in achieving a high Level of Detail (LoD) in iVR experiences.

The LoD defines how closely a 3D model resembles its real counterpart [53]. In CH, accurate models are needed for precise observation, particularly when based on photogrammetry. Managing LoD is especially important on standalone HMDs, which have limited computational power, making optimization essential to avoid cybersickness [17] and enhance user interaction [54]. The modeling procedure followed the reconstruction of the Isis of Clunia, with additional low-poly models added, notably the Clunia theatre captured via aerial photogrammetry and optimized. The Isis model was rigged for animations. Texturing used atlases to improve performance and audio was post-produced for volume equalization and effects. Finally, all assets were integrated into the development engine, using precomputed lighting for enhance performance.

The result is an optimized iVR experience that improves UX and faithfully represents heritage assets. The Blender add-on LoDCalculator, which provides an indicative score of the LoD of a 3D model, gave the models a score of 5/5 [55]. *Figure 7* summarizes the development and optimization process, showing phases from source acquisition to asset creation and implementation in the development engine, with sources and processes indicated by gray dashed rectangles.

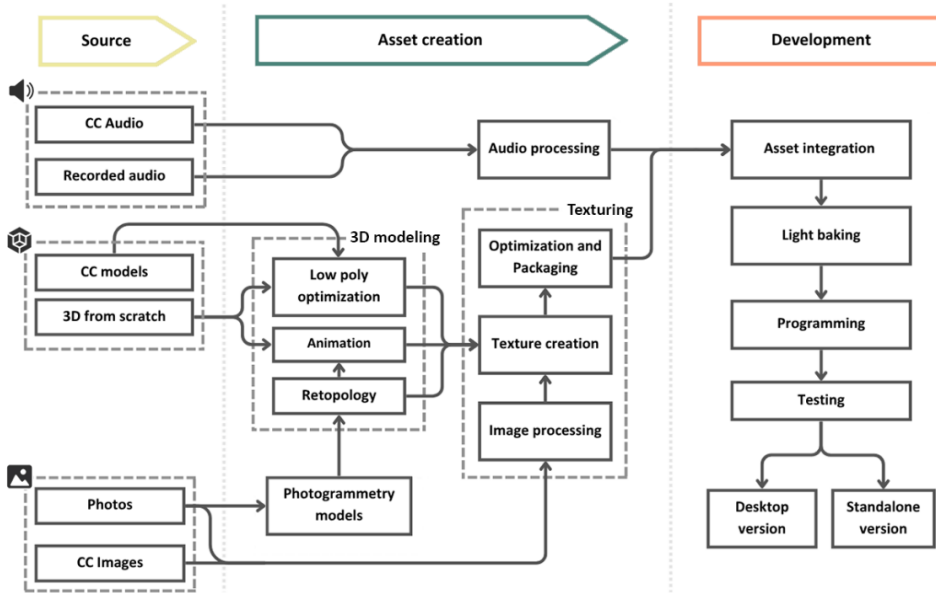


Fig. 7 Summary of the development procedure. The phases are shown horizontally. Gray dashed-line rectangles indicate the type of source and the software used

3.3 Design and development of the video

The Isis of Clunia model was used to create a complementary video shown to the control group. The video runs for 4 minutes 10 seconds with English and Spanish subtitles for enhanced accessibility. It conveys the same knowledge as the iVR experience, previously described in *Section 2*.

The video format means that what users see and hear can be fully controlled, enabling condensed information and additional visual reinforcement. So, the video slightly expands on the historical content and reorganizes it linearly: origins and cult, iconography, and then the characteristics of the sculpture. In *Figure 8*, some frames of the video can be seen. Advantages of the video format against the iVR experience include easier production, lower cost, and simpler use. However, interaction, immersion, satisfaction, and engagement are reduced compared to iVR. All video resources were created using a similar procedure to the one shown in *Figure 7*, though final engine integration was replaced by editing the clips.

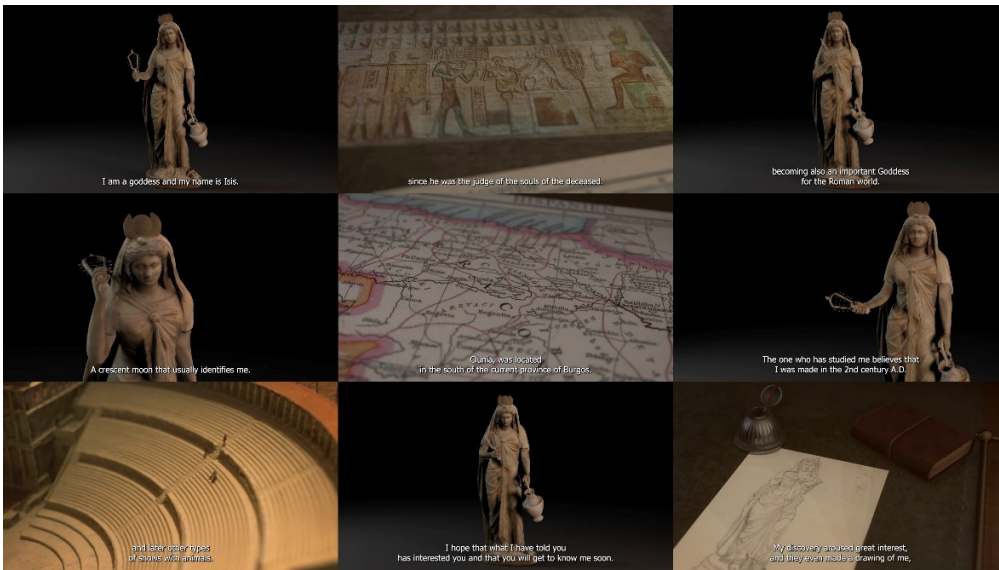


Fig. 8 Frames from the video of the Isis of Clunia with English subtitles

4. Evaluation procedure

The iVR experience and the video were evaluated using a three-phase procedure, collecting objective and subjective data before, during, and after the experience. The assessment was conducted in multiple sessions, due to the large, and demographically diverse sample. The procedure had been validated for iVR evaluation in prior research [56]. The characteristics of each evaluation phase are summarized in *Figure 9*. The characteristics of each instrument are described horizontally, while the order of the phases and the tests included in each one are presented vertically. The 3 phases are described below in detail. The questionnaires used are available in *Annex II*. Lastly, the individual sessions are also explained.

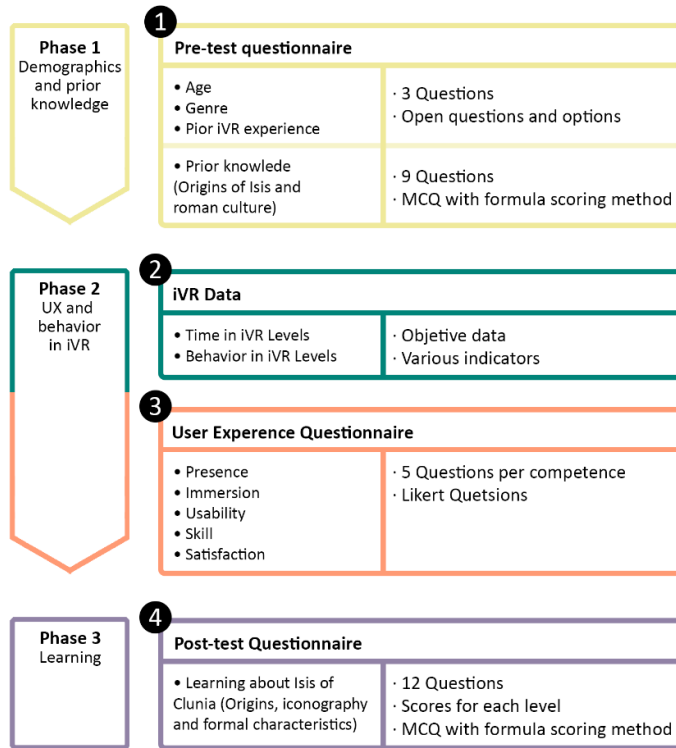


Fig. 9 Summary of the evaluation procedure. The test characteristics are shown horizontally, and the order of the tests and their related phases are shown vertically

4.1 Phase 1: Demographics and prior knowledge

This phase took place just a few minutes before the iVR or video experience and collected demographic and prior knowledge data through a 12-item questionnaire. The first 3 questions covered age, gender, and prior iVR experience, with iVR experience assessed through four predefined options. The remaining 9 Multiple-Choice Questions (MCQ) tested knowledge on Isis's Egyptian origins, worship, and Roman culture. MCQs were chosen because of their suitability for assessing study-unit knowledge [57]. Formula scoring was applied to reduce guessing bias [58], with correct answers adding 1 point and incorrect ones subtracting 1/3. Scores were normalized using Min-Max (0–10) normalization.

4.2 Phase 2: UX and behavior in iVR

During this phase, user behavior and UX data were collected exclusively for iVR participants. This phase took place during and few minutes after the iVR experience. Each of the first four levels (Level 5 served as an epilogue) was evaluated using two

measures: time in seconds to complete the level and a specific behavioral indicator, resulting in a total of four behavior indicators:

- *Level 1:* The time each user took to look at the goddess. A shorter time was considered positive, as it indicated a faster reaction to the 3DoF Isis stimuli.
- *Level 2:* The percentage of activity time. Activity was defined as faster than 10 cm/s. A higher level of activity was considered positive, as it suggested a better understanding of 6DoF mechanics.
- *Level 3:* The number of teleports used. A higher number of teleports was considered positive, as it reflected greater spatial exploration.
- *Level 4:* The number of mistakes made when reconstructing the sculpture. Fewer mistakes were considered positive, as they indicated a better understanding of the task.

UX data were collected with a 25-item Likert questionnaire, with higher scores indicating more positive responses. This approach is commonly used for iVR usability and UX evaluation experiences [26]. The questionnaire assessed five competencies; each measured with five questions: Presence, Immersion, Usability, Skill, and Satisfaction. The average of the five responses represented the value of each competence, while the overall UX score was calculated as the average of 25 responses. Questions were adapted from System Usability Scale [59], the Game Experience Questionnaire [60] and the Presence Questionnaire [61]. These competencies were chosen because they reflect two key features of iVR, immersion and interactivity [62], while satisfaction is a transversal metric across different types of UX questionnaires, whether iVR-based or not.

4.3 Fase 3: Learning

This phase occurred after the iVR or video experience, with timing varying by session. Learning was assessed using a 12 MCQ in a 0 to 10 scale, similar to the one used in Phase 1. In this case, each correct answer added one point out of 12, while each incorrect answer subtracted 1/3. The content of the questions was linked to the topics presented in *Section 2*: the origins and worship of the goddess, her iconography, and the formal characteristics of the Clunia sculpture. Scores were divided into four sub-scores corresponding to the historical content presented in each iVR level and in two sub-scores based on the two phases of the experience: soft interaction (Levels 1 and 2) and hard interaction (Levels 3 and 4); applying all the same formula scoring. Although the video slightly expanded content, the post-test only included material shared by both formats.

4.4 Sessions

A representative sample had to be obtained through several sessions. *Figure 10* shows images from each session, labeled with their corresponding number. The characteristics of these sessions are detailed below:

- *Session 1:* Held in November 2024 at the University of Burgos, involving 30 first-year students from the Bachelor in History and Heritage at the University of Burgos. Most of them experienced the iVR experience, while those with some form of visual or motor disability that prevented them from fully enjoying the iVR experience [20] watched the video instead. Participation in this evaluation was part of their coursework. In this session, Phase 3 took place one week after Phase 2. This session contributed half of the data for the young demographic.
- *Session 2:* Held in March 2025 at the University of Burgos, involving 15 third-year students from the same bachelor program, also as part of their coursework. This group only experienced the iVR experience. In this session, Phase 3 was conducted one week after Phase 2. This session provided the other half of the data for the young demographic.
- *Session 3:* Held in March 2025 at a cultural center in the Burgos region, involving 42 volunteer students from art history courses for older adults who only experienced the iVR experience. In this session, Phase 3 took place a few minutes after Phase 2. This session provided data for the older demographic in the iVR group.
- *Session 4:* Held in April 2025 at the Museum of Burgos over three consecutive days, involving 115 volunteer school students who experienced the iVR experience. A portion of the sample watched the video instead, including some with motor disabilities that prevented them from fully enjoying the iVR experience [20]. In this session, Phase 3 was conducted a few minutes after Phase 2. This session contributed the data for the child demographic.
- *Session 5:* Held in May 2025 at the Museum of Burgos, involving 8 volunteer students from art history courses for older adults who only watched the video. In this session, Phase 3 was conducted one week after Phase 2. This session provided data for the older demographic in the video group.
- *Session 6:* Held in June 2025 at the University of Burgos, involving 5 volunteer students from the Bachelor in Video Game Design at the University of Burgos who only watched the video. In this session, Phase 3 took place a few minutes after Phase 2. This session provided data for the young demographic in the video group.

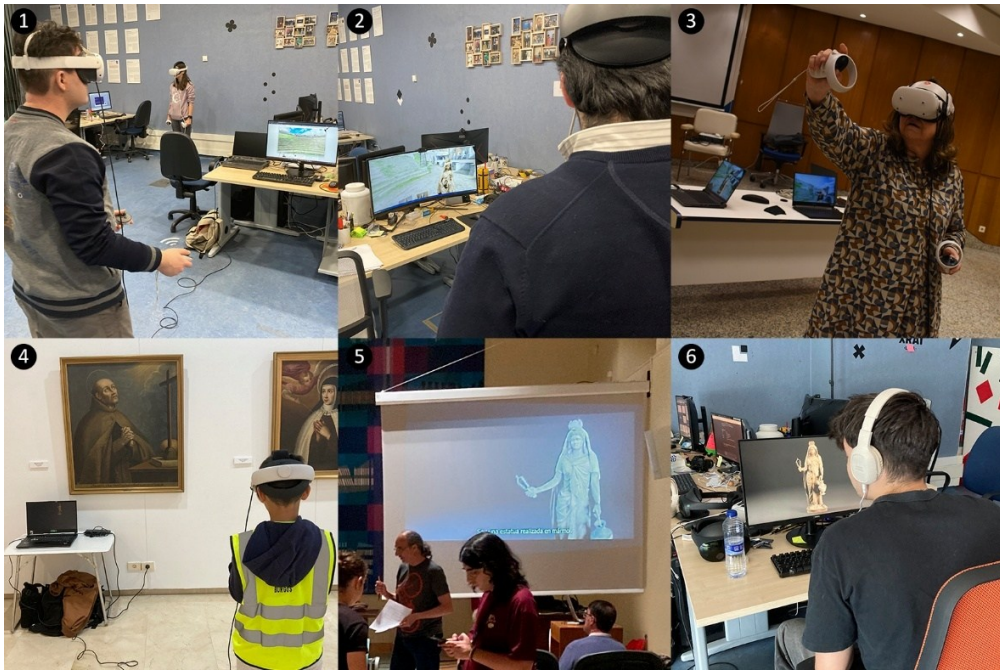


Fig. 10 Images of users in each of the sessions. The image number corresponds to the session number

A one-week interval between experience and post-test was applied, whenever possible, as is recommended [63]. Initial sessions with university students meant better sample control, but other sessions occurred during one-off events, risking participant loss, particularly in Session 4 before the school holidays. Most of the sample (123 users) performed their experience at the Museum of Burgos, but some of the sessions were conducted at convenient locations for the participants, due to the logistical challenges of a multi-phase evaluation and the need to maximize user numbers.

5. Results and discussion

The results were organized by age group, due to the age differences in the sample: Kid group (Session 4), Young group (Sessions 1, 2, and 6) and Senior group (Sessions 3 and 5). The sample was also divided by device: iVR and video.

Of 215 evaluated users, 44 were excluded, leaving 171. Exclusions were due to missing data, copied answers, or irrational (troll) behavior, the latter identified as scoring 1 on all Satisfaction questions. Most exclusions in the Kid group resulted from data loss or copying, complicated by children's higher activity levels [64]. Troll behavior appeared in the Young group, that was called to participate as part of their

class content, likely due to lack of intrinsic motivation [65]. All data are included in *Annex III*. Results are presented by evaluation phase, followed by a summary and this section closes with the derived *Best practices* for iVR design.

5.1 Phase 1: Demographics and prior knowledge

Table 1 shows total sample numbers, age, gender distribution, prior iVR experience, and pre-test results in terms of Mean (M) and Standard Deviation (SD). iVR experience was rated from 0 to 4, while pre-test scored between 0 to 10.

Table 1. Summary of demographic data divided by age group and device

Age group	Device	N	Age		Genre		Prior iVR experience		Pre-test	
			M	SD	M %	F %	M	SD	M	SD
Kid	Both	82	9.02	0.68	59%	41%	1.24	1.21	2.93	1.84
	iVR	63	8.98	0.71	54%	46%	1.33	1.26	2.94	1.92
	Video	19	9.16	0.60	74%	26%	0.95	1.03	2.90	1.60
Young	Both	41	20.7	2.72	68%	32%	1.27	1.18	6.48	1.88
	iVR	32	20.2	2.13	63%	37%	1.09	1.09	6.90	1.61
	Video	9	22.8	3.67	89%	11%	1.89	1.36	4.98	2.09
Senior	Both	48	68.2	7.42	21%	79%	0.40	0.61	5.52	2.51
	iVR	40	68.7	7.62	20%	80%	0.45	0.64	5.45	2.67
	Video	8	66.0	6.28	25%	75%	0.13	0.35	5.88	1.55

The age groups were homogeneous regarding device, with 20% of users in the video condition. Considering age, the average of the age groups effectively represents the three chosen demographics. Kid group averages around 9 years old, placing them in the “concrete operational” cognitive stage, characterized by sufficient logical and cognitive abilities but a need for many sensory stimuli [18]. At that stage, they can use iVR devices, but under adult supervision [66]. The average age of the Young group was around 20 years old, representing young adults, the most studied demographic in iVR research [16] Finally, the average age of the Senior group was over 60 years, which according to the World Health Organization can be classified as elderly [67]. Age group sizes were sufficient for significance, except for the video users in the Young and the Senior age groups, which were only indicative due to their limited size (<20 participants).

Clear trends regarding age differences emerged and are summarized in *Figure 11*. It shows the number of users, gender distribution, average age, pre-test score, and prior iVR experience for each age group, with deviation lines indicating standard deviation. Kid group showed a balanced gender ratio (41% male / 59% female), while Young group were mostly male (68%) and Senior group predominantly female (79%). Gender disparities between the groups were in all likelihood due to the context of their formation. Kid group is the largest, was drawn from a primary school setting expected to have gender balance. Young group were from a smaller and more

specialized class, making gender bias due to class size more likely. Lastly, reports indicated that courses for older adults, which includes the Senior group users, tended to be mostly female students [68]. Previous iVR experience is also related to age, being generally low across all age groups (close to 1 on the scale) meaning that participants have only used iVR once or twice before. The Kid group had limited prior exposure due to their low age. Young group, composed of humanities students, might express less interest in iVR technology than students studying in other fields [69]. Finally, older adults, like Senior group users, often exhibit more skepticism towards new technologies [17]. Among the age groups, the Senior group stands out for having the lowest prior iVR experience, below 1. Prior knowledge varies notably by age group, reflecting their academic backgrounds, a key factor in group formation: being primary students (Kid group), bachelor students (Young group) and attending history courses (Senior group).

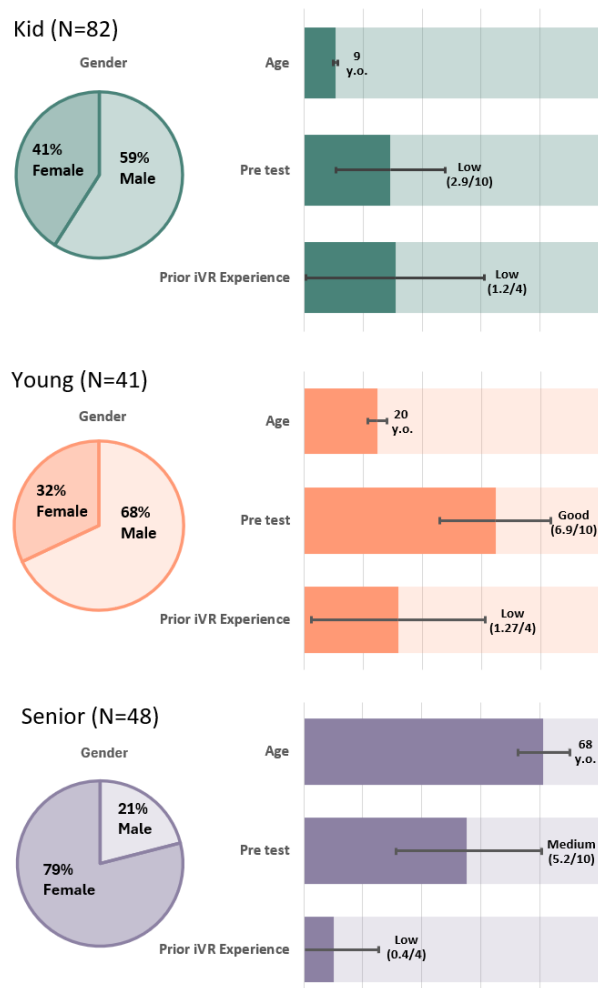


Fig. 11 Summary of the demographic data by age group

5.2 Phase 2: UX and behavior in iVR

The UX results are presented in *Figure 12*, separated by age groups. Only the iVR results are analyzed, as it was the only device evaluated in Phase 2. The X-axis first displays the overall UX score, followed by the scores for each competence. The Y-axis shows the average value of each score, with an expanded scale for better visualization. Significant differences between one age group and the other two, based on Analysis of Variance (ANOVA), are indicated with an asterisk. Additionally, significant differences within each age group, according to their prior iVR experience, are also marked with an asterisk followed by (iVRXP).

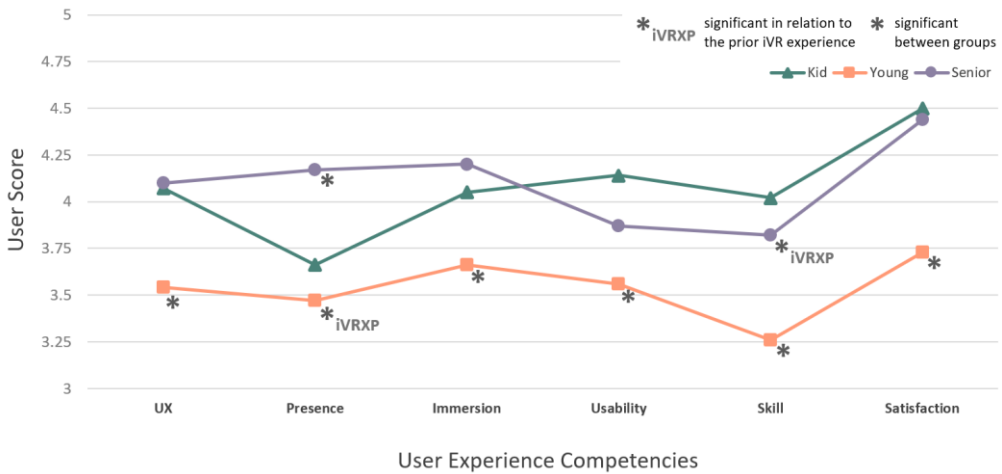


Fig. 12 Average results of UX and related competencies by age groups. Results marked with an asterisk indicate significant differences with respect to the other groups, while those marked with an asterisk followed by "iVRXP" denote significant differences within each group based on prior iVR experience

The information in *Figure 12* is completed in *Table 2*; it shows the ANOVA results for age group comparisons and within-group differences by prior iVR experience. Welch's ANOVA was employed, as Levene's test results indicated that some variables violated the homogeneity of variance assumption [70]. For each group, the p-values (p) and effect sizes (η^2) are reported below in *Table 2*. Significant values are marked with an asterisk (<0.05) and highly significant values with two asterisks (<0.01).

Overall, UX scores were high (*Figure 12*), with a mean close to 4 out of 5 across competencies, particularly for Kid and Senior groups. The highest-rated competency across all groups was Satisfaction, which aligns with common outcomes in iVR research [71]. In contrast, the lowest-rated competency overall was Skill, except in the case of the Kid group. That lower score may reflect the frequency and variety of

interactions within the iVR experience, which could challenge some users by offering limited time for adaptation [22]. The Kid group exception may be explained by children's generally higher tendency toward interaction [38]. The Young group was the only one that consistently exhibited lower values across all competencies, with UX scores only slightly above satisfactory (≈ 3.5). Many of those values were statistically significant with high effect sizes, as can be seen in *Table 2*. Several factors may explain this divergence. First, the novelty effect appeared weaker for the Young group, as they reported the highest levels of prior iVR experience. Additionally, this demographic typically shows lower motivational values compared to children [15] and older adults [23]. Finally, the perceptions of the UX among the Young group, who were participating as part of their coursework rather than voluntarily, may have been negatively influenced by a lack of intrinsic motivation [65].

Table 2. *p-values and effect sizes from ANOVA, comparing age group combinations and prior iVR experience within each group*

Groups	UX		Presence		Immersion		Usability		Skill		Satisfaction	
	p	η^2	p	η^2	p	η^2	p	η^2	p	η^2	p	η^2
All	<.001**	0.176	<.001**	0.230	0.008**	0.123	0.014*	0.117	<.001**	0.214	0.001**	0.180
Kid - Young	<.001**	0.186	0.252	0.020	0.024*	0.085	0.007**	0.143	<.001**	0.243	<.001**	0.244
Kid - Senior	0.849	0.000	<.001**	0.126	0.258	0.013	0.070	0.039	0.146	0.021	0.650	0.002
Young - Senior	<.001**	0.176	<.001**	0.230	0.008**	0.123	0.014*	0.117	<.001**	0.214	0.001**	0.180
Kid (iVR XP)	0.759	0.004	0.986	0.000	0.456	0.024	0.635	0.010	0.910	0.000	0.729	0.005
Young (iVR XP)	0.132	0.138	0.038*	0.302	0.135	0.134	0.696	0.012	0.176	0.128	0.357	0.048
Senior (iVR XP)	0.683	0.076	0.442	0.170	1.000	0.000	0.570	0.171	0.025*	0.607	0.750	0.047

Note. ANOVA Welch (significant *, highly significant**)

These results showed that perceived UX was higher for both the Kid's and the Senior groups, though with differing emphasis. Interaction-related competencies (Usability, Skill) were more positively rated in the Kid group, while immersion-related competencies (Immersion, Presence) were rated higher in the Senior group. These findings align with prior research emphasizing children's strong preference for exploration [47], and older for immersion and presence [17], [72], particularly in environments with naturalistic aesthetics such as the theater of Clunia [22]. The competencies most influenced by prior iVR experience were Presence and Skill. The users of the Young group with less prior iVR experience significantly increased their Presence, as did the members of the Senior group with Skill, in both cases with very high effect sizes.

Analysis of prior iVR experience further characterizes the age groups, showing significant differences with high effect sizes across all UX competencies, as shown in *Table 2*. Young group showed fewer interaction difficulties compared to other age groups [23], so prior experience mainly boosted Presence rather than Skill. Prior experience in the Senior group, which was already experiencing high Presence [17], impacted Skill more than Presence. Those differences reflected a general trend: a

preference for interaction for the Kid group, and for immersion for the Senior group. The Young group, while more balanced across competencies, reported an overall lower perception of UX.

The second analysis refers to the results of behavior indicators in the iVR experience. *Table 3* displays the average and standard deviation for each age group based on level-specific behavior indicators and post-test scores. Although post-test data are not properly a behavior indicator, level-specific scores are included here due to their relevance in relation to behavior. Overall iVR results are also reported, except for behavior, given the distinct nature of these measures.

Table 3. *M and SD values for each age group across all level indicators, as well as the overall results of the entire experience*

Age group	Indicator	Level 1		Level 2		Level 3		Level 4		Total	
		M	SD	M	SD	M	SD	M	SD	M	SD
Kid	Time	58.0	0.00	93.6	59.9	110	57.5	137	56.4	417	98.2
	Behavior	14.6	9.42	0.37	0.16	12.5	10.1	0.94	1.44	N/A	N/A
	Post-test	4.29	3.86	2.79	2.27	3.89	3.45	3.67	3.30	2.95	2.06
Young	Time	58.0	0.00	82.2	61.8	141	80.9	121	53.8	421	146
	Behavior	11.3	3.50	0.48	0.17	18.7	16.8	0.53	0.98	N/A	N/A
	Post-test	8.33	2.71	5.73	3.04	7.55	3.23	5.11	3.50	6.37	1.82
Senior	Time	58.0	0.00	141.7	88.6	178	113	226	127	623	212
	Behavior	19.5	14.0	0.29	0.15	12.8	15.7	0.63	1.21	N/A	N/A
	Post-test	7.92	3.00	4.45	2.92	5.04	3.91	4.42	3.62	5.04	2.12

The results of the iVR experience indicators are shown in *Figure 13*: one radar chart for each of the four levels. Each chart displays the scores of the age groups across the level's indicators: time (bottom right), behavior (bottom left), and post-test (top). The radar chart values were computed using Z-score normalization, so that indicators of different natures may be compared by representing the number of standard deviations from the average [73]. For that reason, the radar charts are presented without scale, since they lose relevance in the context of Z-score normalization. Higher values (i.e., outer points on the radar) were interpreted as follows:

- *In the post-test*, higher scores indicated greater learning outcomes and were therefore considered positive [74].
- *For the time indicators*, shorter completion times were considered favorable, as they suggest more efficient problem-solving [75].
- *The behavior indicators* were interpreted according to the descriptions provided in *Section 4.2*.

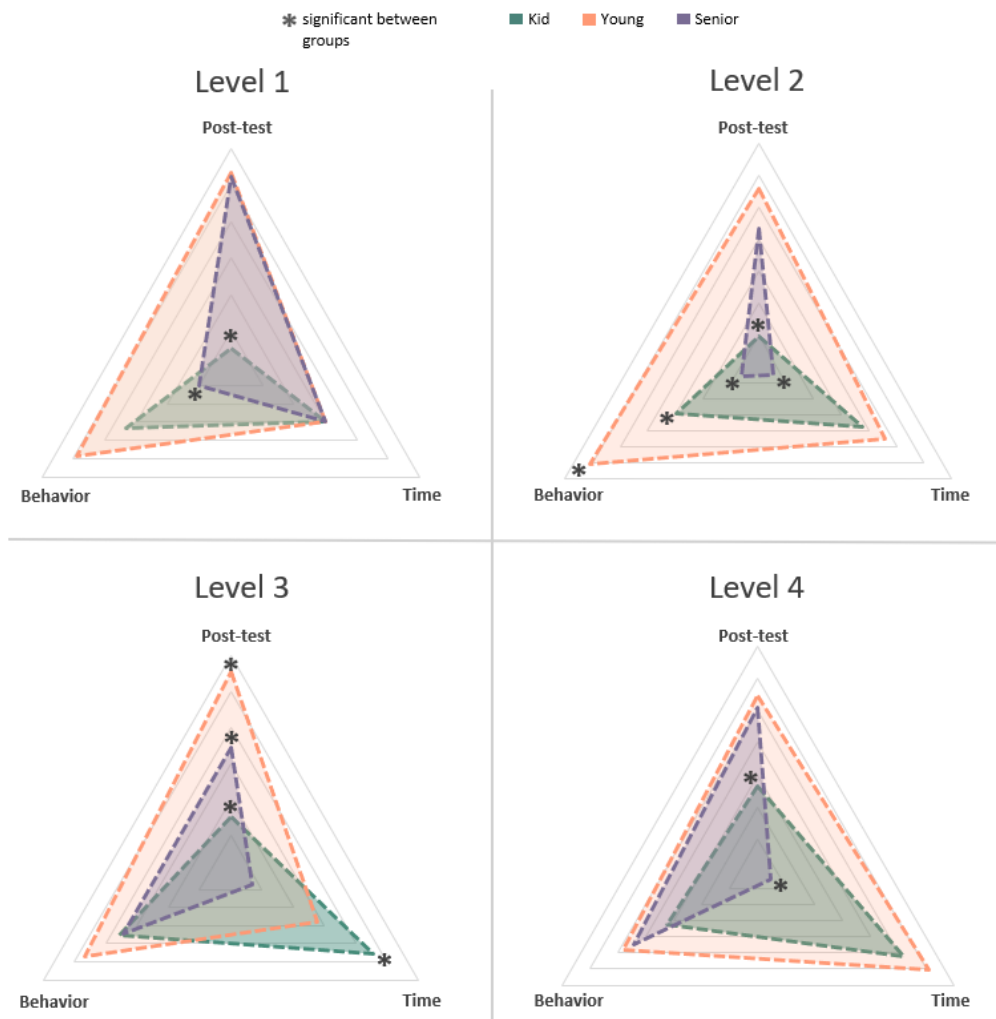


Fig. 13 Summary of the indicators for each level, divided by age group. For each level, time indicators are shown in the bottom right, behavior indicators in the bottom left, and post-test scores at the top. Statistically significant differences between one group and the others are marked with an asterisk

Behavior indicators with statistically significant or highly significant differences between one group and the others according to ANOVA are marked with an asterisk. Welch's ANOVA was used due to violations of the homogeneity of variance assumption in some cases. Table 4 completes the data included in Figure 13. It shows the full ANOVA results, including the p-values and the effect sizes, for all possible age group combinations. No time data were analyzed for Level 1, as the duration was fixed for all users. Similarly, no analysis was performed on the total behavior due to the heterogeneous nature of the behavioral metrics. Significant values are

marked with an asterisk (<0.05) and highly significant values with two asterisks (<0.01).

Table 4. *p-values and effect sizes from ANOVA, comparing age group in level indicators*

Group	Indicator	Level 1		Level 2		Level 3		Level 4		Total	
		p	η^2	p	η^2	p	η^2	p	η^2	p	η^2
All	Time	N/A	N/A	0.004	0.147	0.002**	0.186	<.001**	0.248	<.001**	0.356
	Behavior	<.001**	0.181	<.001**	0.248	0.170	0.056	0.255	0.033	N/A	N/A
	Post-test	<.001**	0.324	<.001**	0.282	<.001**	0.190	0.003**	0.125	<.001**	0.471
Kid - Young	Time	N/A	N/A	0.392	0.012	0.059	0.073	0.177	0.028	0.907	0.000
	Behavior	0.015	0.066	0.004**	0.131	0.064	0.078	0.110	0.030	N/A	N/A
	Post-test	<.001**	0.260	<.001**	0.283	<.001**	0.199	0.003**	0.112	<.001**	0.453
Kid - Senior	Time	N/A	N/A	0.004**	0.147	0.002**	0.186	<.001**	0.248	<.001**	0.356
	Behavior	<.001**	0.181	<.001**	0.248	0.170	0.056	0.255	0.033	N/A	N/A
	Post-test	<.001**	0.324	<.001**	0.282	<.001**	0.190	0.003**	0.125	<.001**	0.471
Young - Senior	Time	N/A	N/A	0.001**	0.140	0.111	0.036	<.001**	0.292	<.001**	0.250
	Behavior	<.001*	0.220	<.001**	0.280	0.134	0.035	0.718	0.002	N/A	N/A
	Post-test	0.897	0.000	0.241	0.016	0.036**	0.049	0.728	0.001	0.079**	0.035

Note. ANOVA Welch (significant *, highly significant**)

The three age groups showed clear differences across all levels, most of statistical significance with high effect sizes, supporting earlier findings on UX. The average iVR completion time was about 8 minutes, with each level taking progressively longer due to increasingly complex interactions. Behavior indicators differed between age groups, but user behavior became more similar in the hard interaction phase (Levels 3 and 4) likely due to the waning novelty effect [76]. Additionally, behavior indicators were mainly movement-based in the soft interaction phase (Levels 1 and 2), while they depended on understanding the mechanics in the hard interaction phase. Also, post-test scores varied: Level 2 had lower scores than Level 1, Level 3 had higher scores, which dropped again in Level 4.

The Kid group completed levels quickly and showed high behavior indicators, especially in the soft interaction phase, but had low post-test scores. An exception occurred in Level 4, where behavior decreases but post-test performance improved compared to previous levels. Those findings align with previous research highlighting children as a highly active and spontaneous age group [64], explaining their elevated behavior scores and reduced completion times, particularly in the soft interaction phase. Both the p-values and the effect size of the ANOVA analysis for behavioral indicators by gender within each age group are presented in Table 5. ANOVA revealed significant gender differences in behavior for boys and girls within those levels, with boys being more active, supported by moderate effect sizes. This outcome is further supported by studies identifying boys as generally more restless than girls [77]. In the Young group, gender differences at Level 1 were not robust due to few female participants. The Kid group's low post-test scores reflect their

prior knowledge, while improved results in Level 4 may result from repeated reconstruction attempts and higher interactivity, which enhancing learning [78].

Table 5. *p-values and η^2 from ANOVA comparing behavior with the gender of each group*

	Kid's genre		Young's genre		Senior's genre	
	p	η^2	p	η^2	p	η^2
Level 1 Behavior	0.056	0.103	0.002**	0.277	0.538	0.044
Level 2 Behavior	0.025*	0.082	0.958	0.000	0.064	0.372
Level 3 Behavior	0.425	0.011	0.988	0.000	0.368	0.107
Level 4 Behavior	0.264	0.022	0.571	0.011	0.722	0.010

Note. ANOVA Welch (significant *, highly significant**)

The Young group shows notable results across all measures, as can be seen in *Figure 13*; with the largest inter-group differences at Level 2. Those differences decreased at later levels, particularly by Level 4. While Level 3 showed some significant differences, these are mostly due to post-test scores with minimal effect sizes between Young and Senior groups. The above results agree with previous research indicating that young adults generally faced fewer difficulties when interacting in iVR [23] in part for being the most studied demographic in iVR research [16]. The peak differences at Level 2 reflect a strong novelty effect, highlighting the importance of gradually introducing new interactions for better acclimation [22]. As the differences between the levels diminished, progression through to higher levels functioned as a tutorial that reduced disparities between groups [79].

The Senior group is characterized by lower behavior indicators and longer completion times. Although with good post-test results, they were slightly lower than the results of the Young group. It was foreseeable, as higher prior knowledge generally led to better outcomes [80], but it showed that despite the interaction challenges of iVR [22], the learning rates among seniors were not significantly affected. A result that is aligned with evidence that their cognitive performance in iVR is comparable to younger users [23]. The largest differences with other groups, at Level 2, had diminished by Level 4.

Finally, an Analysis of Covariance (ANCOVA) was performed, to evaluate the correlation between UX and behavior indicators. The results are summarized in *Table 6* (p-values and effect size) where age group is a fixed factor across behavior indicators and UX competencies, with Level 2 being the only level showing significant correlations with UX and Immersion.

Table 6. *p-values and η^2 from ANCOVA of behavior indicators at each level in relation to UX competencies*

Covariates	Level 1 Behavior		Level 2 Behavior		Level 3 Behavior		Level 4 Behavior	
	p	η^2	p	η^2	p	η^2	p	η^2
UX	0.520	0.717	0.041*	0.028	0.426	0.005	0.958	0.000
Presence	0.521	0.003	0.107	0.017	0.656	0.002	0.272	0.009
Immersion	0.739	0.001	0.015*	0.039	0.233	0.010	0.719	0.001
Usability	0.461	0.004	0.082	0.020	0.876	0.000	0.493	0.004
Skill	0.295	0.008	0.222	0.010	0.134	0.016	0.662	0.001
Satisfaction	0.877	0.000	0.112	0.017	0.332	0.007	0.481	0.004

Note. ANCOVA Welch (significant *, highly significant **) Fixed Factor: Age group

5.3 Phase 3: Learning

Learning was evaluated by comparing pre and post-tests results and searching for differences between the first (soft interaction) and the second (hard interaction) phases of the iVR experience. The learning outcomes are summarized in *Tables 7* and *8* and *Figure 14*. *Tables 7* shows the average and standard deviation for the pre-test, post-test, soft interaction phase (Levels 1–2), hard interaction phase (Levels 3–4), and the absolute learning gain relative to the pre-test. The post-test was not divided into four sections, as too few questions would produce unreliable results, especially with formula scoring. The results are presented all together and by age group, distinguishing by device (iVR or video). *Table 8* presents ANOVA results (p and η^2) across age group and device combinations, using Fisher's ANOVA, as the Levene's test confirmed homogeneity of variance. Finally, *Figure 14* presents Phase 3 results by age group and the total. The X-axis shows columns for post-test, soft interaction, and hard interaction scores, separated by device (iVR left, video right), with pre-test scores marked by a black dashed line. The Y-axis represents the test scores.

Table 7. *M and SD values for the total sample and for the combinations of age groups and device used in the Phase 3 results*

Age group	Device	Pre-test		Post-test		Soft interaction phase		Hard interaction phase		Learning total		Learning Soft interaction phase		Learning Hard interaction phase	
		M	SD	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD
Total	Both	4.51	2.57	4.35	2.50	5.10	2.85	3.78	2.77	-0.16	2.50	0.59	2.79	-0.73	2.90
	iVR	4.62	2.68	4.38	2.46	5.02	2.92	3.88	2.70	-0.24	2.50	0.40	2.86	-0.74	2.89
	Video	4.08	2.12	4.20	2.65	5.40	2.56	3.43	3.01	0.12	2.51	1.32	2.44	-0.66	2.99
Kid	Both	2.93	1.84	2.89	2.11	3.48	2.50	2.67	2.40	-0.04	2.58	0.54	2.72	-0.26	2.96
	iVR	2.94	1.92	2.95	2.06	3.26	2.52	2.89	2.39	0.01	2.57	0.32	2.82	-0.05	2.95
	Video	2.90	1.60	2.69	2.32	4.18	2.36	1.93	2.37	-0.21	2.66	1.28	2.26	-0.97	2.98
Young	Both	6.48	1.88	6.09	1.84	6.82	2.22	5.39	2.39	-0.39	2.19	0.34	2.53	-1.08	2.70
	iVR	6.90	1.61	6.37	1.82	7.03	2.29	5.71	2.29	-0.53	2.03	0.13	2.43	-1.19	2.50
	Video	4.98	2.09	5.09	1.62	6.05	1.85	4.26	2.52	0.11	2.76	1.07	2.89	-0.72	3.47
Senior	Both	5.52	2.51	5.34	2.17	6.41	2.34	4.31	2.86	-0.18	2.64	0.89	3.13	-1.21	2.90
	iVR	5.45	2.67	5.04	2.12	6.18	2.33	3.96	2.74	-0.40	2.73	0.74	3.24	-1.49	2.89
	Video	5.88	1.55	6.81	1.85	7.57	2.14	6.04	2.96	0.93	1.91	1.69	2.58	0.16	2.67

Table 8. *p-values and η^2 obtained from ANOVA for the total sample and the combinations of age groups in the Phase 3 results*

Device	Group	Pre-test		Post-test		Soft interaction phase		Hard interaction phase		Learning total		Learning Soft interaction phase		Learning Hard interaction phase	
		p	η^2	p	η^2	p	η^2	p	η^2	p	η^2	p	η^2	p	η^2
Total	All	<.001**	0.367	<.001**	0.326	<.001**	0.305	<.001**	0.170	0.768	0.003	0.632	0.005	0.131	0.024
	Kid-Young	<.001**	0.453	<.001**	0.361	<.001**	0.303	<.001**	0.226	0.461	0.004	0.687	0.001	0.138	0.018
	Kid-Senior	<.001**	0.262	<.001**	0.238	<.001**	0.255	<.001**	0.087	0.763	0.001	0.504	0.004	0.078	0.024
	Young-Senior	0.047*	0.045	0.082**	0.034	0.408	0.008	0.057	0.041	0.694	0.002	0.365	0.009	0.831	0.001
iVR	All	<.001**	0.367	<.001**	0.326	<.001**	0.305	<.001**	0.170	0.768	0.003	0.632	0.005	0.131	0.024
	Kid-Young	<.001**	0.519	<.001**	0.405	<.001**	0.352	<.001**	0.247	0.303	0.011	0.746	0.001	0.065	0.036
	Kid-Senior	<.001**	0.233	<.001**	0.196	<.001**	0.256	0.039*	0.041	0.436	0.006	0.496	0.005	0.017*	0.055
	Young-Senior	0.008**	0.095	0.006**	0.102	0.125	0.033	0.005**	0.107	0.831	0.001	0.385	0.011	0.644	0.003
Video	All	<.001**	0.378	<.001**	0.425	0.003**	0.304	0.001**	0.327	0.575	0.033	0.874	0.008	0.677	0.023
	Kid-Young	0.007**	0.245	0.01**	0.230	0.047*	0.143	0.025*	0.180	0.767	0.003	0.838	0.002	0.843	0.002
	Kid-Senior	<.001**	0.442	<.001**	0.441	0.002**	0.328	<.001**	0.370	0.285	0.046	0.681	0.007	0.361	0.033
	Young-Senior	0.334	0.062	0.060	0.216	0.138	0.141	0.200	0.107	0.497	0.031	0.650	0.014	0.569	0.022
iVR-Video	All	0.267	0.007	0.705	0.001	0.479	0.003	0.386	0.004	0.446	0.003	0.080	0.018	0.876	0.000
	Kid	0.941	0.000	0.635	0.003	0.162	0.024	0.127	0.029	0.738	0.001	0.182	0.022	0.234	0.018
	Young	0.005**	0.183	0.064	0.085	0.246	0.034	0.108	0.065	0.446	0.015	0.333	0.024	0.653	0.005
	Senior	0.659	0.004	0.034	0.094	0.126	0.050	0.059	0.075	0.197	0.036	0.438	0.013	0.144	0.046

Note. ANOVA Fisher (significant *, highly significant **)

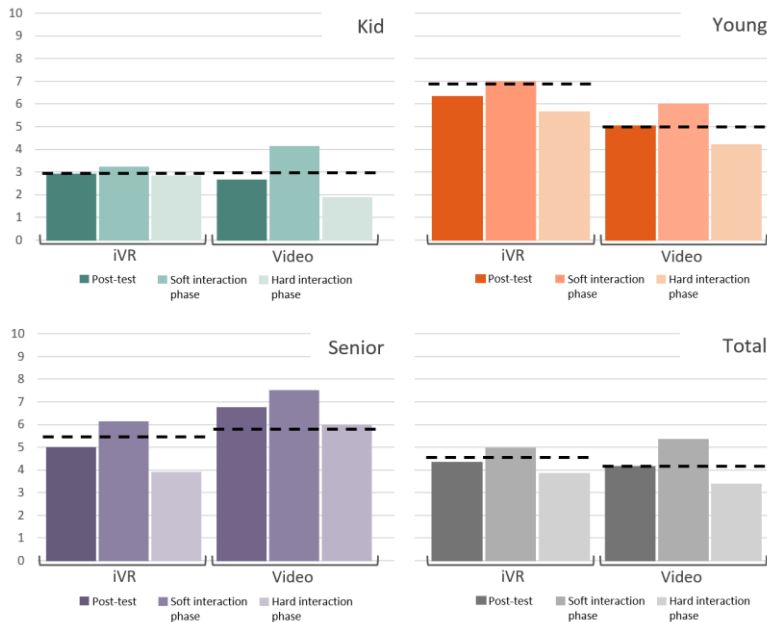


Fig. 14 Summary of Phase 3 results divided by age groups, overall totals, and device used

Some interesting conclusions can be drawn from this statistical analysis. Except for some differences between the Young and Senior groups, the post-test results showed significant differences with high effect sizes, as can be seen in Table 8. Overall, scores were slightly lower than the pre-test, which was foreseeable since the post-test covered more advanced topics such as Isis's iconography, whereas the pre-test focused on her origins and general Roman culture [74]. Scores for the soft

interaction phase were generally higher than for the hard interaction phase, due in all likelihood to increased complexity in Levels 3 and 4 and a renewed novelty effect [14]. The same pattern was also seen among video users, who scored better on soft interaction phase questions. Additionally, questions on the soft interaction phase often addressed Isis's Egyptian origins, a more familiar topic, which also introduced a difficulty bias. Even so, total post-test scores for iVR users were slightly higher overall, except where the video users scored better in the Senior group.

Absolute learning gains were positive in the soft interaction phase but turned negative in the hard interaction phase, explaining the overall slightly lower iVR results. However, in the hard interaction phase, Kid and Young groups still showed better learning in iVR, especially Kid group, whereas Senior group participants performed better with the video, showing even larger differences than in the soft interaction phase. The results of the ANOVA analysis pointed to more significant learning in the Kid group than in the Senior group and nearly more than in the Young group, though with a small effect size, as can be seen in *Table 8*. Despite the higher complexity of the post-test, it suggests that the increased interaction of the iVR was beneficial to the Kid and the Young group, supporting prior findings on children's enhanced learning with interactive experiences [78] and young adults' adaptability to iVR [16]. Besides the poorer learning outcomes for the Senior groups, these levels could improve their satisfaction. *Figure 14* shows that the Kid group maintained similar iVR scores across phases, while the video users had significantly lower scores, although initially better in soft interaction. Senior group users showed lower iVR outcomes, especially in the hard interaction phase, consistent with their known interaction challenges [22], yet they performed better in iVR soft interaction due to a preference for passive, presence-focused experiences [16]. Even though they may have limited iVR skills, their cognitive capacity remained comparable to that of younger adults [23], suggesting that the first half of the iVR experience was suitable for them.

An additional linear regression analysis was conducted to further explore the differences between both phases of the post-test, focusing especially on the iVR users, among whom the most pronounced differences and largest sample size were observed. *Figure 15* presents two scatter plots depicting the normalized learning gain [81] of the iVR users. The left plot illustrates learning outcomes in the soft interaction post-test, while the right plot corresponds to the hard interaction phase post-test. In each plot, the X-axis represents the pre-test score on a scale from 0 to 1, and the Y-axis shows the percentage improvement from pre-test to post-test in the different phases. Trend lines for each group were fitted using second-degree polynomial curves. A jitter of 3% was applied to enhance data visualization. The visual presentation of the scatter plots and the fit indicators of the analysis are

presented in *Table 9*, including R, R², and p-values for each analysis according to age and device group. Regression analyses were conducted from pre-test to soft interaction phase, pre-test to hard interaction phase, and between both phases.

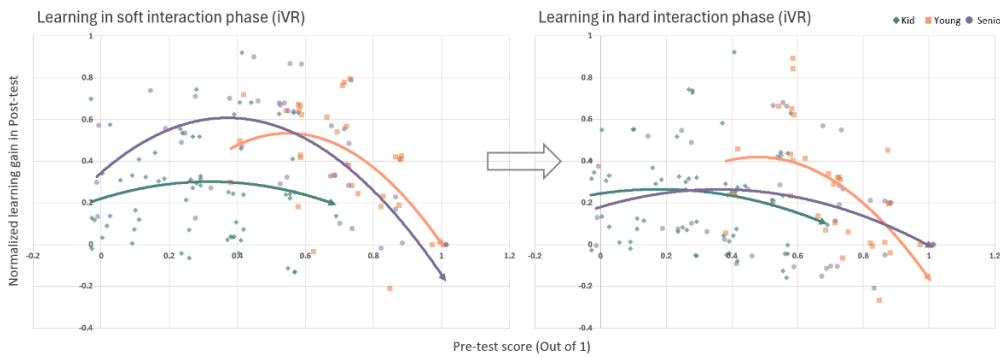


Fig. 15 Scatter plot of normalized learning gain by groups in the soft interaction phase (left) and hard interaction phase (right)

Table 9. Results of the linear regression analysis based on different combinations of age groups and device

Goups	Pre-test - Soft interaction phase			Pre-test - Hard interaction phase			Soft interaction - Hard interaction		
	R	R ²	p	R	R ²	p	R	R ²	p
Total	0.410	0.168	<.001**	0.473	0.224	<.001**	0.428	0.183	<.001**
Total iVR	0.422	0.178	<.001**	0.482	0.233	<.001**	0.432	0.186	<.001**
Total Video	0.359	0.129	0.031*	0.472	0.222	0.004**	0.450	0.202	0.006**
Kid Total	0.043	0.002	0.702	0.244	0.060	0.027*	0.234	0.055	0.034*
Kid iVR	0.075	0.006	0.558	0.215	0.046	0.090	0.238	0.057	0.060
Kid Video	0.095	0.009	0.700	0.398	0.159	0.091	0.378	0.143	0.110
Young Total	0.216	0.047	0.175	0.243	0.059	0.126	0.232	0.054	0.144
Young iVR	0.216	0.047	0.236	0.259	0.067	0.152	0.259	0.067	0.153
Young Video	0.130	0.017	0.739	0.077	0.006	0.844	0.077	0.006	0.843
Senior Total	0.422	0.178	0.003**	0.164	0.027	0.265	0.368	0.135	0.01*
Senior iVR	0.428	0.183	0.006**	0.165	0.027	0.308	0.382	0.146	0.015*
Senior Video	0.442	0.195	0.273	0.049	0.002	0.909	0.025	0.001	0.954

Note. significant *, highly significant **

Some clear conclusions can be extracted from this linear regression analysis. In the soft interaction phase, Young and Senior groups showed a steeply decreasing trend, while Kid group declined only slightly, indicating that users with lower prior knowledge, especially in Young and Senior groups, achieved higher learning gains. Most of the curves remain above zero on the Y-axis, reflecting positive outcomes. In the hard interaction phase, Kid and Young groups patterns remained similar, but the Senior group's curve flattens, reducing gains. Linear regression confirms this shift as statistically significant for Senior iVR users. Overall, curves move closer to zero with more users below it, showing reduced learning gains. These results reinforce the previous conclusions about learning patterns in age groups. Learning outcomes tend to decline in the hard interaction phase, with this change being significant in

both iVR and video users according to the linear regression analysis. While Kid and Young groups maintained their soft-interaction phase patterns, Senior group differed, with lower prior knowledge linked to poorer results and higher pre-test scores associated with better outcomes.

Kid group showed better performance in the hard interaction phase, which perhaps reflected the positive impact of increased interaction on learning [18], though their slightly flattened post-test curve indicates that pre-test scores still influence outcomes. Linear regression shows no clear relationship between phases overall, but in the hard interaction phase, this correlation was stronger with the video condition ($R \approx 0.4$, $R^2 > 0.15$). The hard interaction levels probably had a positive effect on children's learning therefore, despite the relatively flat curve of the Kid group. The tendency for learning gains to decrease as prior knowledge increases is consistent with expectations [81]. Young group followed typical trends, as is the most evaluated demographic [16], suggesting that higher interaction did not negatively affect them, with lower results in the hard interaction phase reflecting increased difficulty. For the Senior group, convergence in performance during later phases among users with less prior knowledge indicates group homogenization, likely due to limited iVR learning, making post-test scores more dependent on prior knowledge and diminishing novelty effects. This led to a stabilization in which users with less prior knowledge felt less motivated, while those with more prior knowledge adapted better to the interaction. In any case, greater prior knowledge accentuated the differences observed among the Senior group users during the levels involving higher interaction.

5.4 Summary and best practices

The iVR experience revealed some usability issues linked to its experimental design, which prioritized research requirements over commercial polish, despite being intended for a museum-like context. These issues were mainly linked to the repeated introduction of new interaction systems, creating a strong novelty effect, especially evident in Level 2, where differences were most pronounced. A more accessible design would rely on fewer, well-introduced interaction types. Even so, user UX scores were high, and post-test results were favorable, often surpassing those of the video condition, indicating that the design was successful and effective for knowledge dissemination. However, for greater effectiveness, the design should also consider the specific needs of different age groups [82]. The three age groups showed significant differences across all evaluation phases, but all shared low of prior iVR experience, an important factor for mass audiences, who usually lack such exposure [41]. Nonetheless, as the iVR experience advanced, group differences tended to diminish, suggesting that in longer sessions the novelty effect fades [76].

Kid group stood out for their strong UX perception, particularly in interaction-related competencies, consistent with prior research [18], [78]. They showed positive behavioral indicators and completed levels relatively quickly, making them ideal users for highly interactive iVR experiences. Within the age group, boys displayed higher activity levels than girls. Although their overall learning outcomes were modest, they began from a similarly low baseline. Importantly, this age group displayed strong interest in interaction, performing better in iVR. While video supported higher learning in the early levels, iVR proved more effective in later stages, reinforcing their preference for this format.

Young group showed a slightly lower but still positive UX perception, possibly due to weaker novelty effects or less participatory attitudes influenced by the evaluation context, all worth considering in experience design for this demographic segment. Their behavioral indicators were the highest across all levels, and they completed the tasks quickly. Those traits highlighted their adaptability, allowing for flexible experience design, especially in the soft interaction phase. However, frequent changes in interaction types triggered a recurrent novelty effect, suggesting that limiting the number of interaction systems might be beneficial. Post-test outcomes were largely consistent with pre-test results, reflecting positive learning. Although video users scored higher, that result may be due to participants without prior history education, who had lower baseline knowledge and greater room for improvement [81]. Moreover, iVR users completed the post-test one week later, which could have influenced results. Overall, iVR can be considered at least as effective as video. No strong preference for specific interaction types emerged, as comparable outcomes were observed across them, offering flexibility in iVR experience design for this age group.

The Senior group was characterized by a strong UX perception, excelling particularly in immersion-related competencies, though scoring lower in those tied to interactivity. Participants with less prior iVR experience achieved notably better Skill outcomes, underscoring the importance of this competency among older adults, who generally have limited prior exposure to iVR [20]. During the iVR experience, they showed weaker behavioral indicators and required more time to complete tasks, though these differences diminished as the levels progressed. Previous studies have highlighted their preference for more passive iVR experiences and their tendency to experience stronger presence [72]. These tendencies were reflected, with higher learning outcomes in the iVR soft interaction phase compared to the video. The Senior group was the only age group to show such a clear advantage in iVR. However, their performance declined in the hard interaction phase, though it was aligned more closely with their prior knowledge. The same pattern may also reflect their preference for naturalistic aesthetics [22], such as the Clunia Theater. Taken

together, these findings suggest that while older users can achieve favorable outcomes in hard interaction settings, but they requires careful introduction and adequate acclimatization time. For shorter iVR experiences a simpler design emphasizing presence and immersion is more suitable.

The iVR experience revealed significant differences compared to the video, consistent with findings from previous research [83]. These differences were most pronounced when leveraging iVR's defining features, immersion and interactivity, with the appropriate age groups, namely Kid and Senior groups. It highlights the importance of tailoring experiences to specific demographics groups and ensuring that iVR content is developed with high LoD and optimization to maximize immersion [80] and interactivity [54]. When these conditions are not adequately met, more established and cost-effective formats, such as video, may prove more suitable. In fact, this study found that learning outcomes in the soft interaction phase were generally higher with video. Although iVR is often associated with greater user satisfaction, video outperformed it in certain aspects, such as soft interaction learning in the Kid and Senior groups. Given that 3D models, commonly employed as foundational resources, can serve multiple purposes, it is advisable to provide a video alternative (or another inclusive format) alongside iVR experiences designed for broad audiences, particularly for reasons of accessibility. In this study, 5% of participants had to rely on video due to disabilities preventing the use of iVR. While more accessible iVR designs are possible, they often diverge substantially from traditional formats intended for mass audiences [84].

The main findings are summarized in two radar charts in *Figure 16*. The first highlights age group differences in behavior, learning (soft and hard), perceived UX, and completion time in the iVR experience. The second compares iVR and video across the most relevant aspects identified in this study. Data were normalized with Z-scores and no scales are shown, similarly to *Figure 14*. In the iVR vs video chart, only learning values are taken from actual data, while the remainder are based on observations. In both charts, outer values represent more positive outcomes, for instance, shorter iVR completion times and lower video-related costs.

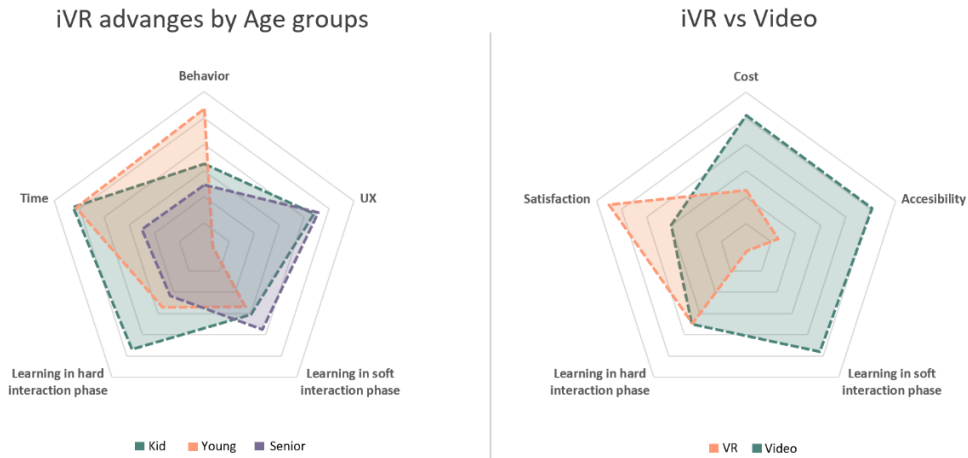


Fig. 16 Summary of the research results. On the left, the advantages of each age group in the characteristics of the iVR experiences are shown. On the right, the advantages of the iVR and video formats are presented

Considering the results of this research, the following series of best practices have been identified for the design and development of iVR experiences aimed at a mass audience and adapted to different age groups:

- When working with 3D models, it is essential to leverage their flexibility to develop complementary and more accessible experiences.
- Using iVR experiences with a mass audience requires more extensive planning due to the increased number of challenges involved.
- For an iVR experience to be effective and preferable over more affordable and accessible technologies, it is necessary to capitalize on its immersive and interactive features.
- It is advisable to focus the iVR experience on a few well-introduced mechanics to avoid inducing novelty effects in users.
- Immersion has proven to be a key factor for all age groups, making it essential to ensure high LoD and optimization in iVR experiences.
- The longer the duration of an iVR experience, the less noticeable the differences between users become, in terms of UX perception and learning outcomes.
- User-adapted design is more effective than a universal approach; however, effective universal experiences can still be created by carefully considering general usability principles.
- High levels of interaction are suitable for children, but due to their agitation, it is necessary to moderate interaction and introduce educational content only after they have acclimated to the experience, especially among boys.

- Young people can adapt to different interaction systems, so the design can be more flexible with this age group.
- Older adults take significantly longer to complete experiences, so it is preferable to design shorter experiences while accounting for their longer completion times.
- Older users prefer and learn more from soft interaction experiences with naturalistic aesthetics; nevertheless, if sufficient time is provided for proper adaptation, more complex experiences can be developed.

6. Conclusions

In this study, the design and evaluation of a CH iVR experience at the Museum of Burgos has been presented. The experience was directed at children, young adults, and elderly, with a video group serving as a control. The iVR experience included four progressively complex levels, so that users could gradually engage with various interaction systems. The design balanced duration, motivation, novelty effect, and potential iVR side effects, supported by a narrative led by the VA, the goddess Isis of Clunia, and careful optimization. The iVR experience and the video were evaluated using a sample of 171 participants distributed across three age groups (Kid, Young, and Senior) through a three-phase assessment: prior knowledge and demographic characteristics, perceived UX and data obtained from the iVR experience and post-experience learning outcomes. The evaluation yielded the following findings.

- *The Kid group* responded enthusiastically to high interactivity, with particularly strong behavioral engagement among the boys rather than the girls. They completed tasks rapidly and interacted confidently. Although their learning outcomes with soft interaction were higher with the video, they ultimately benefited from greater interactivity in terms of both learning and satisfaction. Their high motivation and quick adaptation suggest that interactive formats are suitable for this group, provided that cognitive demands are introduced progressively.
- *The Young group* showed the highest adaptability and the shortest completion times across all levels, demonstrating consistent behavioral performance regardless of interaction type. These attributes indicate a strong potential for engaging with a wide range of iVR designs. However, their UX ratings were more moderate, possibly due to reduced novelty perception or a less involved attitude during testing.
- *The Senior group* displayed a clear preference for soft interaction and tended to place greater value on immersive rather than interactive competencies, which aligned with their higher learning outcomes in such contexts. Although they required more time to complete tasks, they showed notable

improvements over time, underscoring the importance of slower paced design. Older users can benefit substantially when iVR is properly adapted to their preferences, even in more interactive formats.

- *Comparisons between iVR and video* indicated that, if the advantages of more accessible and familiar formats such as video are to be surpassed, then the key strengths of iVR, namely immersion and interactivity, must be intentionally and effectively leveraged through optimization and design. Video remains a valuable and practical alternative whenever those conditions cannot be ensured, or when addressing audiences with accessibility constraints. Nevertheless, tailoring experiences to user characteristics will yield better learning outcomes and engagement. Universally designed experiences can also succeed when they are grounded in strong usability principles and carefully considered design strategies.

Future research will be focus on exploring the design patterns identified within each age group to develop experiences that are specifically tailored to their needs. In that regard, further investigation will also address strategies for the rapid reduction of the novelty effect during iVR experiences, a factor that has proven to be highly relevant for facilitating user adaptation across different demographic profiles.

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Data availability. Annexes are provided at the following link: <https://xrailab.es/2025/09/18/annex/>

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Part III

Discussion and outlook

PREFACE

This part consists of two chapters. The first chapter discusses the conclusions of this thesis. The second chapter proposes a series of future research lines based on its results. Both the conclusions and the future lines address the goals outlined in *Chapter 2 of Part I*.

In this thesis, an approach to the optimization of iVR experiences for the dissemination of CH reconstructions has been undertaken from three different perspectives corresponding to the thesis goals: analytical, practical through the development of 3D models and the design of iVR experiences, and evaluative. These perspectives are grounded in the three phases of creating an iVR experience and aim to optimize the key features of iVR: presence and interactivity. The conclusions derived from these perspectives are discussed below, following the same structure.

1.1 Review of iVR experiences for the dissemination of CH reconstruction

In *Result 1*, a critical review of the literature on iVR experiences for the dissemination of CH reconstruction was conducted to understand the current state of the topic, its possibilities, limitations, and the most promising future research lines. The use of iVR technology in this research area is evolving rapidly. Since 2013, the number of publications has progressively increased, reaching a peak in 2018. Although its growth has been less pronounced in subsequent years, the proportion of studies published in journals rather than conference proceedings has continued to rise, indicating signs of academic maturation. Nevertheless, the number of conference papers remains high, and fewer than half of the studies include an experimental evaluation. The taxonomy used in the studies is also unclear, with keywords including both iVR research and 2D screen-based research. These signals suggest that there is still considerable room for full academic consolidation. These publications also reveal a strong interdisciplinarity in authorship: while most first authors come from technical departments, second authors are frequently affiliated with departments in historical or archaeological studies.

Most of the scientific production is concentrated in Europe, primarily focused on reconstructions of the Roman or contemporary periods, likely due to the greater availability of archaeological remains and documentary sources. Reconstructions based on less reliable sources are also common, particularly those corresponding to different periods of the Middle Ages. In this context, the characteristics of CH have

a major influence on reconstruction. On the one hand, the quality of documentation often facilitates the creation of reconstructions with a high LoD. However, iVR experiences developed from these reconstructions are typically 3DoF, probably due to the difficulties of managing the high LoD of 3D models that usually originate from photogrammetry, thus pointing to a clear limitation in this regard. On the other hand, reconstructions based on more limited documentation are usually created through 3D modeling. Although they often feature a lower LoD, the environments tend to be larger and offer more possibilities for interaction.

Most iVR experiences are not designed for a specific audience and they are usually explorative 6DoF experiences without interaction. This represents one of the weakest aspects of the research area, since designing effective iVR experiences that consider their audience and purpose produces better results. Among those that are aimed at a specific audience, two purposes stand out: musealization and education. Musealization experiences are aimed at a very broad audience. These typically employ reconstructions with a high LoD and reliable documentation, but are usually very simple and with limited interaction, many of them being 3DoF. In contrast, educational experiences are aimed at a more restricted and smaller audience, usually students. These iVR experiences display a much higher degree of interaction and a larger 3D environment, but they use 3D models with a lower LoD.

Among iVR technologies, the most established is 3DoF, with clear design patterns and stable publication frequency over the years. These are usually passive experiences, typically controlled by head movement, although they are gradually evolving toward interaction systems that allow users to choose different scenarios to visualize. They may sometimes include characters, but these are not virtual agents since they are pre-recorded. These experiences are usually run on standalone HMDs, both high- and low-end. Thanks to their pre-captured environments, they can achieve high LoD with few difficulties, due to their very low level of interaction. For this reason, they are widely used in museum experiences, where their high LoD and low interactivity can even be considered an advantage, as it facilitates the use of the technology.

Conversely, 6DoF technology is much more diverse and has evolved significantly over the years. These are often explorative or explorative interaction experiences, which is expected since these iVR modalities allow users to explore lost CH environments; one of the great advantages of iVR. Interaction is usually absent, but it is becoming increasingly common, as is the inclusion of secondary locomotion systems such as teleport locomotion. They may also include virtual agents, either to populate the reconstructions or to serve as guides for users. While these experiences were initially run on desktop HMDs with external trackers, technology has evolved to internal tracking and, in recent years, to standalone HMDs, which provide greater

user comfort. Thanks to these characteristics, they are the experiences that best exploit the features of iVR. However, they are less widely used due to the greater difficulty of development and implementation compared to the more established 3DoF. In this regard, the interdisciplinary nature of the research area has led to a stronger presence of simpler development engines in creating these experiences. Nevertheless, there is a clear trend in this technology toward greater interaction, realism, and user comfort through standalone HMDs.

Besides the state-of-the-art, this analysis highlights four major limitations in the development and design of iVR experiences for the dissemination of CH reconstructions: 1) the lack of a clear purpose in experience design which limits personalized and context-adapted designs; 2) the technical challenges of managing high LoD, resulting in a preference for 3DoF experiences; 3) the difficulty of incorporating interactivity in 6DoF experiences, especially the intended for broad audiences; and 4) insufficient and poor assessment. These limitations result in the frequent use of 3DoF experiences, where low interactivity and LoD are less restrictive. However, they constrain the development of 6DoF experiences, which are the technology best suited to fully exploit the core features of iVR. This phenomenon is particularly evident in musealization contexts, where challenges related to space, time, and large user numbers are especially significant.

1.2 Development of optimized 3D models for CH reconstruction

As observed in *Result 1*, the development of 3D models, particularly the management of LoD, represents a major limitation in the optimization of iVR experiences. A high LoD enables greater immersion and presence, as well as a more accurate representation of CH. However, its management is challenging due to the high computational cost. In this sense, interdisciplinarity is one of the main limitations for development in this research area, as poor management of technical resources can lead to issues with visualization, performance, or usability. This situation results in many iVR experiences being 3DoF with low interactivity, especially those with photogrammetry-based models, due to the difficulty of managing their computational cost. Therefore, it is essential to optimize this aspect, by creating frameworks and tools that are accessible in terms of cost and ease of use to foster progress in the discipline. To this end, this thesis has approached the subject through different approaches: 1) the creation of an add-on for the straightforward classification of 3D models based on their LoD (presented in *Result 2*); and 2) a procedure for creating, optimizing, and validating 3D models for CH reconstructions (presented in *Result 3*).

On one side, the development of add-ons for 3D software has proven to be an effective strategy, as it facilitates development and allows for seamless implementation within the software (Grande et al., 2024). In this regard, the add-on presented in *Result 2* stands out for providing an accessible tool that enables the classification of 3D models based on their LoD within one of the most popular 3D modeling software. In addition, complements the taxonomy proposed in *Result 1* to support decision-making in iVR experience development. Its operation is based on the analysis of two key parameters of 3D models: their surface and the quality of their materials. Its outcomes have been supported by a subjective evaluation carried out by both professionals and 3D modeling students, offering LoD estimates with acceptable error ranges. Developing such tools in add-on format not only extends the functionalities available to users but also simplifies their distribution and installation, as they run directly within the software that users are already familiar with. This strategy is particularly valuable in interdisciplinary research such as CH reconstruction.

On the other side, the procedure presented in *Result 3* addresses the process of creating, optimizing, and validating a 3D model for the virtual reconstruction of a partially destroyed CH asset. This involves not only 3D modeling techniques but also data acquisition methods such as photogrammetry. As shown in *Result 1*, these techniques are crucial for the development of 3D models for CH reconstruction, since many of these models are initially generated this way due to their high fidelity to the existing archaeological remains. However, they often present challenges in managing the LoD and computational cost. In this regard, optimization processes are essential to achieve a high LoD while maintaining the performance of the experience. However, this process involves a high level of technical complexity, an issue that *Result 3* has not been able to solve. In addition, inevitably entails some loss of surface and material fidelity, two of the most important factors affecting the quality of a 3D model. It is crucial to consider this aspect when designing a dissemination experience, both during 3D model validation and its implementation. Regarding this, it is important to employ the most appropriate methods for 3D model development and optimization. Among the various capture techniques, photogrammetry stands out as a straightforward method that faithfully preserves the radiometric properties of a 3D model. This is particularly relevant for optimization, since much of the simplification of the 3D model occurs at the surface level.

Finally, as observed in *Result 3* and *4*, virtual agents can be useful for enhancing engagement in iVR experiences, but its creation is more complex than that of other types of 3D models, as it must be capable of movement, especially when a personalized outcome is desired. In this regard, incorporating interaction into 3D

models increases the complexity of their creation. This situation poses a barrier to integrating interactivity in iVR experiences for the dissemination of CH reconstructions. All these development and optimization challenges are further amplified when designing for standalone HMDs due to their lower technical capabilities, representing a limitation for creating iVR experiences.

1.3 Design of iVR experiences for the dissemination of CH reconstructions

As detected in *Result 1*, the design of iVR experiences evolves alongside technological advancements and their increasing affordability, progressively moving toward greater interaction. Nevertheless, there are clear design patterns for 3DoF and 6DoF experiences exhibiting a general tendency toward passive interaction. Specifically, many passive 3DoF experiences still exist, making this the most established iVR modality in this research area. Therefore, it is necessary to optimize the iVR design to implement higher levels of interaction, enhancing the engagement of the iVR experience. In *Result 1*, a taxonomy was developed to facilitate decision-making in iVR design. To implement this outcome, two iVR experiences were developed to optimize the design of the iVR experiences: 1) a baseline one, based on the most established design patterns (presented in *Result 3*); and 2) a more experimental one, designed to incorporate different types of interaction (presented in *Result 4*).

The first experience is presented in *Result 3*, a simple iVR experience for standalone HMDs, designed to test the 3D model of the Isis of Clunia in a musealization context. In this experience, users could observe and explore in a very limited way the two versions of the sculpture, the original and the reconstructed. This experience was 6DoF and allowed slightly more freedom than the 3DoF experiences analyzed in the literature. Nevertheless, its interaction was completely limited, with only an optional active-movement locomotion system within a very restricted area. Its simple design, based on the established design patterns identified in the state-of-the-art, achieved good user satisfaction and perceived usability, as well as enabling a smooth experimental test. As a result, this consolidated design homogenized the differences between users, making it necessary to apply clustering techniques to extract distinctions among them. The evaluation of this iVR experience provided highly valuable insights: 1) in iVR experiences designed for a mass audience, such as musealization context, age and prior iVR experience have a significant impact; and 2) iVR features, particularly the level of interactivity, must be adapted accordingly. These variables were further investigated in *Result 4*, where

their outcomes were compared with those of a video, providing a set of valuable guidelines for the design of iVR experiences.

In *Result 4*, dissemination iVR experience with a more experimental design composed of multiple levels with increasing interaction was designed and evaluated. In this experience, users engaged in the history and iconography of the statue of the goddess Isis of Clunia through a narrative led by the 3D model of the sculpture acting as a virtual agent. Users progressed through the four types of iVR experiences, each incorporating a higher degree of interactivity, with the aim of facilitating their acclimatization. Prior iVR experience and, particularly, age shown as highly significant factors during iVR interaction. These factors appeared more prominently than in *Result 3*, where clustering was required to make them visible, showing that a design with greater interaction generates higher friction for users. However, these differences tended to diminish as the experience progressed.

As observed in *Result 4*, children were highly active and quick in the iVR experience, especially among boys. Their high motivation and rapid adaptation suggest that interactive formats are suitable for this age group, provided that cognitive demands are introduced progressively. Their learning rates compared to other groups were low, but due to their age they start from a lower baseline. Young adults were able to complete the experience quickly and efficiently, showing high adaptability, albeit with slightly lower satisfaction. This is a relevant factor for designing for this age group, as they are not easily influenced. Their learning rates were high in iVR, especially among those with lower prior knowledge. Older adults took longer to complete the experiences and were better suited to iVR with low interaction, as this group favors experiences with a greater focus on immersion, preferably in naturalistic environments. This trend was especially clear in their learning, which was much higher at the more passive levels. Nevertheless, with proper acclimatization, they can engage with more complex experiences. In general, knowledge acquisition was good across all groups, at least matching the levels achieved with video, although each group performed better with iVR designs tailored to their specific needs. This indicates that a well-designed iVR experience can be a valuable tool for knowledge transmission due to its higher engagement, even if it is not specifically designed as an educational application.

Ultimately, optimizing the core aspects of iVR, namely presence and interactivity, is essential to creating experiences with greater potential than those offered by alternative technologies. In this regard, aspects such as the design of the iVR experience, the LoD, and the performance of the experience are key factors. The management of these factors greatly influences usability and also the achievement of high immersion. In particular, the latter feature is highly relevant as it affects all types of experiences, whether interactive or not, and is especially important for

certain age groups, such as older adults. iVR by itself is not inherently beneficial for the dissemination of CH reconstructions; a design specifically adapted to this purpose is required. Otherwise, more established technologies may provide greater benefits in CH dissemination, such as higher accessibility. In this sense, 3D models stand out as a highly flexible resource, since the same model can be used in different types of iVR experiences or other technologies as video. Moreover, interactions should be introduced with sufficient time to allow users to adapt to them, and their number should be limited, particularly for users with difficulties, such as older adults. In this context, interactions involving active movement are the most suitable as they represent the most intuitive option for users of all types.

1.4 Evaluation of iVR experiences for the dissemination of CH reconstructions

Result 1 revealed that iVR assessments in CH research remain scarce. Approximately half of the studies do not conduct any assessment, and among them, fewer than half use control groups, multi-phase assessments, data collection from iVR experiences, or inferential statistical techniques. Moreover, most of them focused on the usability of the experience. While this is an important factor, it is transversal to any type of iVR experience, and there was no clear objective in the evaluation. This phenomenon is particularly evident in iVR experiences without a clear purpose. In this regard, the most common evaluations are usability assessments, typically using a single post-experience questionnaire with a small sample. In contrast, iVR experiences for musealization and education show better results, especially in education, since a higher level of specialization in the experience entails an evaluation with a clearer purpose and methods. In these cases, evaluations can also be observed that go beyond usability, with assessments divided into multiple phases to allow longitudinal analysis and involving large samples with control groups. To address this issue, two evaluations were conducted in this thesis, in *Result 3* and *4* respectively.

On the one hand, *Result 3* performed an evaluation of usability in the Museum of Burgos as part of a temporary activity. This evaluation consisted of a questionnaire post-experience. On the other hand, *Result 4* conducted an evaluation of usability and learning rates of an iVR experience in both application contexts: at the Museum of Burgos as part of a temporary activity, and at the University of Burgos as educational content for one of its bachelor programs. This evaluation involved a large sample and a control group, comparing the effectiveness of iVR with a more established technology, video. A three-phase procedure was used (before experience, during and after), incorporating questionnaires, data collection from the iVR

experience, and inferential statistics for data analysis. This approach allowed for robust conclusions, demonstrating the effectiveness of the procedure. However, it also revealed some weaknesses.

Firstly, in the phase conducted at the Museum of Burgos, it was necessary to exclude several participants due to confusion in the questionnaires and missing data, highlighting the challenges of conducting evaluations in an open context such as a museum. This was not only due to the context of the evaluation, as the complexity of the iVR experience and the different phases of the assessment played a key role. The evaluation in *Result 3* was conducted under similar conditions without these complications; however, the iVR experience was much simpler and was assessed solely through a post-experience questionnaire. Lastly, in the phase conducted at the University of Burgos, there were no data losses, but some participants showed a lack of motivation due to the activity being part of their class content which resulted in a poorer perception of usability. Despite the effectiveness of a robust data collection method, both contexts present limitations in their application. In the case of musealization, data collection from iVR experiences is a highly effective strategy, as it is transparent to the user and does not increase the time or complexity of the evaluation. In contrast, questionnaires can be problematic, especially longer ones or those divided into several phases. In the educational context, both data collection from iVR experiences and questionnaires are effective strategies due to higher control over the evaluation, but it is necessary to carefully consider and maintain student motivation.

Overall, the evaluation of iVR experiences remains one of the discipline's weakest points; however, despite its limitations, it can and should be improved to achieve academic consolidation.

This thesis has contributed to answer some of the questions posed, yet many others remain open, along with new ones that have emerged from its findings. The research presented represents only an overview of the potential of iVR for the dissemination of CH reconstructions, and further investigation is still required. As with the conclusions, the proposed future research lines correspond to the goals of this thesis, as outlined in *Chapter 2 of Part I*. The following sections detail these future lines following the same structure.

2.1 iVR experiences for the dissemination of CH reconstructions

Most iVR experiences for CH reconstructions lack a defined application context, making it necessary to design purpose-driven experiences, such as for education or musealization, that effectively its features and advantages. Nevertheless, these classifications remain broad and offer many possibilities. This thesis proposes two future research to improve the application of iVR and immersive technologies in these areas: 1) the use of collaborative iVR environments to improve the control of experiences in museums; and 2) the use of multi-scale environments to enhance visual learning.

On one side, one of the main challenges in museums is the lack of control and isolation of many users due to the nature of iVR, which makes it difficult to introduce complex interactions. To address this issue, further research is needed in collaborative iVR environments. With this technology, users are not fully isolated from each other or from the organization, which facilitates the management of activities and events. This approach would allow multiple users to coordinate within the same activity without losing control. In this regard, an iVR experience could be developed in which multiple users explore a reconstructed environment, being able to see and interact both with each other and with the exhibition guide. This research direction is particularly challenging due to the new design difficulties involved in ensuring usability and user coordination across different types of settings,

particularly taking into account the variable size of the installation space and the locomotion systems.

On the other side, one of the main advantages of iVR for CH education is its ability to deliver first-person visual information that would otherwise be inaccessible. However, this potential is not fully exploited under standard viewing conditions. Research into alternative visualization settings, such as multi-scale environments, could expand the possibilities of this technology by offering multiple perspectives through scale manipulation. For instance, users could explore a reconstructed city at ground level while also observing its urban layout. In this way, not only would the scale of the spaces be better understood, but each viewpoint would also provide different information. Nevertheless, these environments raise usability challenges, including the risk of cybersickness; in addition to the technical challenges of managing a very large 3D environment. This research line therefore represents a design and optimization challenge, requiring attention to factors such as interaction design, embodiment as well as the diverse needs and characteristics of users.

2.2 3D models development for CH reconstructions

There is a wide range of tools for creating 3D models with different LoDs and computational demands. Yet, they require significant expertise, a challenge in multidisciplinary contexts. This complexity increases in iVR, particularly for standalone HMDs. To address these issues, this thesis proposes three future research directions: 1) the use of 3D representation techniques such as Gaussian Splatting to enhance immersion and optimization; 2) the development of user-friendly tools for optimizing large-scale 3D environments; and 3) the creation of tools for the straightforward development and implementation of adaptable virtual agents for better engagement.

Firstly, the use of passive 3DoF experiences, often based on pre-captured environments, is a well-established trend, especially in the commercial sector due to their ease of development and user-friendliness. However, their lack of stereoscopy results in low immersion and, therefore, reduced presence. To improve these experiences, future research is needed on the use of 3D representation techniques such as Gaussian Splatting. With these techniques, it is possible to generate 3D environments from pre-captured 360° settings, allowing stereoscopic visualization, although movement remains limited. These 3D representations can also be combined with 3D models in 6DoF experiences, reducing the computational load of distant elements. In this regard, a neural network system could be developed to estimate a depth map that allows splatting into 3D Gaussians, adding depth to the

environments. This future line, in addition to the complexities arising from relying on a new technology, must also be adaptable to the usability requirements of this research area, creating accessible tools.

Moreover, increasingly powerful HMDs and computers will make the development and implementation of 3D models easier despite their computational demands. However, the greater complexities of iVR, especially in large environments like city reconstructions, prolong this challenge. Therefore, techniques and frameworks are needed to optimize 3D models, particularly for large-scale environments. In this regard, future research is needed to develop tools that allow the prioritization of 3D models and the estimation of LoD based on their visual weight for the user, considering features such as distance from the viewpoint, contrast, material resolution etc. This would facilitate decision-making and the optimization of large environments. Similarly, tools are needed to optimize and compress assets with lower visual weight using techniques such as automatic retopology or texture atlas merging. These tools should be validated with users and professionals through subjective evaluations, user exploration analysis or eye-tracking. Additionally, they must meet high usability standards to ensure their practical application in CH reconstruction research; for example, as add-ons for popular modeling software.

Finally, virtual agents are valuable design elements in iVR, serving as guides or scene inhabitants and enhancing engagement. However, their interactive nature makes them difficult to create and adapt to different scenarios or reconstructions. To address this problem, research is needed on virtual agents that allow asynchronous and easy recording of actions for their implementation as guides or inhabitants in a reconstruction. This requires the development of a system that enables straightforward recording on customizable characters that can be included in various types of iVR experiences. For example, allowing the recording of actions in iVR directly from a development engine or 3D software via an add-on. In addition to the technical challenges, this study must produce a user-friendly tool that can adapt to the requirements of this research area.

2.3 iVR design for the dissemination of CH reconstructions

The inclusion of interactive elements in iVR is increasingly common and necessary to foster engagement and interactivity. However, proper design requires considering usability and user differences. To overcome this limitation, this thesis proposes two future research directions: 1) the creation of iVR experiences adaptable to users in real-time to improve usability and interactivity; and 2) the design of new locomotion systems based on active movement to enhance exploration.

Although tutorials are useful for reducing differences between users, they are often insufficient and can become an additional element complicating the implementation of iVR experiences. Therefore, future research is needed on reducing the novelty effect during iVR experiences and on adapting these experiences to individual users. This requires investigating the implementation of Artificial Intelligence systems that dynamically adjust design parameters in real time based on user metrics such as cognitive load. A similar system can also be applied to the training of virtual agents that assist users, helping to reduce the novelty effect. To achieve this, it would be necessary to create a model that, based on signals collected during the iVR experience, can make decisions applicable to different types of iVR experiences: enabling the visualization of additional assets, unlocking new types of interaction, providing hints and assistance to users, etc. This research presents significant technical challenges due to the processing of parameters and the generation of changes within the iVR experience, which entails a substantial computational load.

Lastly, active-movement locomotion systems provide greater comfort for all kinds of users in iVR design. However, these systems are limited by the available space for the iVR experience. Therefore, further research is needed on secondary locomotion systems based on gestures or movements that can overcome this limitation. This requires analyzing the movement and exploration patterns of different types of users in order to develop a system that is efficient for a diverse range of users. To this end, a fully active movement-based experience would need to be created, allowing users to move and explore in diverse ways. In this way, data could be collected for the development of locomotion systems based on the patterns of a large and diverse sample. Such research would improve both movement and interaction in 6DoF experiences but poses considerable design challenges.

2.4 iVR evaluation for the dissemination of CH reconstructions

Evaluation is one of the aspects that requires further research due to its current underdeveloped state. Beyond improving sample size, control groups, and evaluation phases, additional strategies must also be explored. To address this challenge, three future research directions are proposed: 1) the development of modular questionnaires to improve the convenience of evaluations in uncontrolled environments; 2) the development of real-time data extraction to enhance evaluation comfort and enable more comprehensive data analysis; and 3) the implementation of Artificial Intelligence and Machine Learning techniques to improve evaluations and development of iVR experiences.

The use of questionnaires can present challenges in uncontrolled environments such as museums, particularly for longer experiences. Therefore, research is needed to develop modular questionnaires that allow independent or combined assessment of key competencies. This approach would enable the adaptation of questionnaire complexity to the experience and evaluation context. To this end, a modular questionnaire could be developed including the most used competencies and extensively validated across different types of iVR experiences. This would allow testing its effectiveness for each type of iVR experience, both jointly and modularity. This research would pose a challenge for conducting the evaluation, as testing all variables would require a very large sample.

Data extraction during iVR experiences has proven valuable and is essential for future research lines such as real-time environment adaptation and cognitive load assessment. Further study of techniques like eye-tracking and biosensors could provide additional types of data to complement existing analyses. It is necessary to consider which signals are most valuable and the least invasive way to collect them. In a research area such as the dissemination of CH reconstructions, a method must be implementable without inconveniencing users, with eye-tracking sensors (included in some HMDs) and biosensors such as wristbands being particularly promising due to their user comfort. Therefore, it is necessary to investigate which method allows the extraction of the most valuable signals with minimal inconvenience for the user, comparing the effectiveness of different types of sensors. This research presents both technical and economic challenges, as it requires additional hardware beyond the HMD.

Finally, data analysis using Artificial Intelligence and Machine Learning is an increasingly popular technique. It is also necessary for other development lines, such as real-time environment adaptation. Although this is cross-cutting research that can be applied in many phases of iVR study, it is particularly valuable for data analysis. One possible application in this research is the creation of tools to extract data from iVR experiences, which can then be analyzed in notebooks or dedicated software with a simple interface. In this way, the use of these techniques can be democratized, improving the evaluation of iVR experiences in this area.

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