From Digital Reconstruction to Immersive Education: Virtual Reality Cultural Heritage Experience

Matteo Caponi [1], Cecilia Ruggieri [1], Francesco Di Stefano [1], Ramona Quattrini [1], Roberto Pierdicca [1]

[1] Dipartimento di Ingegneria Civile, Edile e Architettura, UNIVPM, Ancona, Italy
matteocaponi4@gmail.com; c.ruggieri@studenti.univpm.it; f.distefano@staff.univpm.it; r.quattrini@staff.univpm.it; r.pierdicca@staff.univpm.it;

Keywords: Virtual Reality, Cultural Heritage, Education, User Experience Design, Immersive Guided Learning.

Abstract

The digital transformation of Cultural Heritage is increasingly shifting from documentation-oriented practices toward immersive, learner-centered educational experiences. In this context, Virtual Reality (VR) represents a powerful medium for enhancing accessibility, engagement, and knowledge acquisition. This paper presents the development of an immersive VR educational experience focused on Roman architecture, using the old theatre of Palmyra (Syria) as a case study. The project aims to transform high-quality digital reconstructions of endangered and partially destroyed heritage into an interactive learning environment, preserving collective memory while fostering cultural awareness. The methodological framework builds upon existing photogrammetric reconstructions of Palmyra, generated through spherical photogrammetry, which are optimized for real-time visualization and integrated into a VR ecosystem developed in Unity. A five-level architecture, based on comprising infrastructure, platform, content, interaction, and application, guides the design process, ensuring both technical performance and pedagogical effectiveness. The virtual environment incorporates semantic enrichment, interactive navigation, contextual information panels, and guided thematic paths to promote experiential and active learning. The study highlights how immersive VR applications can bridge digital reconstruction and education, shifting users from passive observers to active participants. The proposed approach demonstrates the potential of VR-based cultural experiences as inclusive and sustainable tools for heritage education, as an added value that complements traditional, non-immersive teaching methods. Future work will focus on evaluating learning outcomes and user experience through an experimental framework involving students, comparing virtual and real-world educational activities.

1. Introduction

The digital transformation of Cultural Heritage (CH) has progressively expanded from documentation and visualization toward experiential, learner-centered forms of engagement. In recent years, immersive technologies such as Virtual Reality (VR), along with Augmented Reality (AR) and Mixed Reality (XR), have enabled new educational paradigms that place users at the center of cultural experiences. Rather than passively observing heritage artifacts or sites, learners can now interact with reconstructed environments, exploring cultural narratives through participation and embodied experience (Silva and Teixeira, 2021); (Innocente et al., 2023). This shift supports deeper cognitive and emotional involvement, reinforcing learning through exploration, discovery, and contextual immersion.

The widespread adoption of digital heritage solutions during and after the COVID-19 pandemic further underscored the importance of accessibility, inclusion, and remote learning in both education and cultural dissemination (Lu et al., 2022). As physical access to museums and heritage sites became limited, virtual tours emerged as viable and sustainable alternatives (Nespeca et al., 2023), capable of democratizing cultural knowledge beyond geographical and socio-economic constraints. Beyond functioning as substitutes for on-site visits, VR-based CH experiences increasingly contribute to alternative forms of didactic learning, supporting structured educational pathways that extend traditional classroom practices.

In this context, VR enables immersive guided learning, where users are not merely visitors, but active learners engaged through narrative-driven, interactive, and pedagogically informed experiences. Such environments allow learners to explore cultural spaces under guided frameworks that support reflection, contextual understanding, and knowledge construction. At the same time, immersive VR experiences serve as powerful tools for raising awareness about the preservation and enhancement of CH, particularly for sites and artifacts that are endangered, inaccessible, or at risk due to environmental, social, or political factors (Hajirasouli et al., 2021). By fostering emotional engagement and experiential understanding, VR can promote cultural sensitivity and long-term awareness of heritage conservation issues.

Consequently, VR-based CH applications represent not only instruments for documentation and preservation, but also platforms for meaningful educational innovation aligned with the United Nations 2030 Agenda, particularly Goals 4 (Quality Education) and 10 (Reduced Inequalities). This study investigates how digital reconstruction can evolve into immersive educational environments by emphasizing User Experience Design (UXD) as a key factor in the effectiveness, engagement, and sustainability of VR systems for CH education. Through the lens of immersive guided learning, the research explores how UX-driven design choices can enhance learning outcomes, accessibility, and user satisfaction within immersive educational contexts.

2. Related Works

Recent studies in immersive education have increasingly examined the comparative role of real, virtual, and mixed environments in supporting learning processes. (Mitrakas and Tsihouridis, 2025) provide a structured analysis of inquiry-

based learning across real, virtual, and mixed reality settings, demonstrating that the simultaneous and bidirectional interaction between physical and digital elements can significantly enhance motivation, conceptual understanding, and learning outcomes. Their findings underline how mixed and immersive environments are most effective when learning activities are guided through structured tasks, worksheets, and pedagogical scaffolding, rather than relying solely on free exploration. Although this work is situated within science education, it offers important methodological insights for CH contexts, particularly regarding the value of guided interaction and the complementary role of real and virtual experiences.
Similarly, (Richter et al., 2025) explore immersive XR applications for paleontology education, emphasizing the role of 3D digitization, virtual museums, and customizable XR environments in enabling experiential learning where direct access to real artifacts is limited. Their work highlights how immersive VR and XR applications can support observation, exploration, and engagement with complex cultural and scientific objects, while also addressing challenges related to usability, performance, and accessibility. However, learning is largely framed as exploratory and experience-driven, with limited emphasis on explicit instructional guidance or narrative-driven learning structures, leaving open questions regarding how immersive environments can systematically support knowledge construction beyond engagement and visualization.
Building upon these educational foundations, previous research has widely investigated the use of VR, XR, and virtual experiences for the visualization, preservation, and dissemination of CH. Comprehensive surveys, such as (Bekele et al., 2018); (Quattrini et al., 2020), outline how immersive technologies enhance realism, spatial understanding, and accessibility, positioning VR as a transformative medium for cultural heritage communication. A systematic review examines how Digital Transformation Technologies (DTTs) are reshaping museum exhibitions by enhancing design engagement, accessibility, and data-driven visitor experience management (Li et al., 2024). It highlights the current gap in linking specific technologies to concrete application scenarios, particularly the educational one the current paper deals with. More recent contributions emphasize the emergence of XR ecosystems and metaverse-oriented frameworks that integrate immersive technologies into CH education, highlighting standards, architectures, and technological strategies aimed at enhancing user engagement and experiential quality (Anwar et al., 2025); (Frontini et al., 2026). Similarly, virtual museums and Unity-based applications demonstrate how immersive environments can balance cultural authenticity with interactive exploration (Hu and Xie, 2025), while XR-based documentation practices are increasingly adopted to safeguard endangered or lost heritage and promote open-access dissemination (Di Stefano et al., 2022).
Alongside technological development, several studies address the educational potential of immersive CH environments. XR experiences have been shown to foster active learning, emotional engagement, and exploratory behaviors in art and heritage education (Dafiotis et al., 2025); (Puggioni et al., 2021). In parallel, recent research highlights the growing importance of UXD and evaluation frameworks in assessing immersive applications. (Liu et al., 2025) demonstrate that learning effectiveness in CH VR is strongly influenced by the alignment between interaction design, User Experience (UX), and learning objectives, while XR-driven evaluation frameworks seek to measure perceptual realism, engagement, and human-centered interaction (Stacchio et al., 2024). Nevertheless, in many of these works, learning outcomes remain implicit or secondary to usability and engagement metrics.
Despite this extensive body of literature, a significant gap persists in the systematic integration of immersive guided learning within virtual CH experiences. Although prior studies frequently compare learning in real, virtual and mixed environments or emphasize free exploration and visual fidelity, they rarely articulate how immersive virtual experiences can be intentionally designed as pedagogically structured experiences that support reflection, contextual understanding, and progressive knowledge construction. In particular, the educational role of guidance, through narrative, instructional cues, or learning-oriented interaction design, remains underexplored within CH VR experiences.
The present work addresses this gap by framing the virtual experience not merely as a visualization or access tool, but as an immersive guided learning environment for CH. Moving beyond a purely comparative analysis between real-world and VR-based learning, the proposed approach integrates UXD and pedagogical intent to actively engage users as learners rather than passive visitors. By embedding guidance, narrative structure, and reflective interaction into the immersive experience, this contribution extends current research by demonstrating how VR-based experiences can support deeper experiential understanding, foster cultural awareness, and promote long-term sensitivity toward CH conservation and valorization.

3. Materials and Methods

This activity is developed within the EU project XR Culture - eXplore Reuse 3D cultural heritage within the Data Space (https://xrculture.eu/), which defines multiple use cases addressing different application domains. Among these, XR for Education is the specific scenario discussed in this work, serving as a testbed to investigate how immersive guided environments can support educational learning and enhance user engagement in CH contexts.
This research project follows a structured methodological approach, schematically represented through a workflow illustrated in Fig. 1.
The educational experience is intended for students and professionals in the field of CH, within a structured educational context. The main objective is to test and compare XR tools for immersive education with traditional non-immersive teaching methods, in order to evaluate their effectiveness in terms of learning outcomes and user acceptance.
Our goal is to compare learning outcomes, considering both qualitative feedback and quantitative results. Specifically, this scenario will involve a frontal lecture complemented by an immersive XR experience, allowing students to directly engage with digital CH assets. This will be followed by an online survey to gather comprehensive data on their learning vitrual experience. In this scenario, VR is not intended to replace traditional teaching methods, but to act as a complementary tool, enriching the educational experience with immersive guided learning.

3.1 Asset optimization of selected 3D CH asset

The first step of the research is to develop a 3D model, designed to enhance knowledge of Roman architecture. By digitally reconstructing its monuments and space, particularly the Roman Theatre.
The Roman Theatre of Palmyra, in Syria, has been chosen as the selected case study for the educational experiment. The

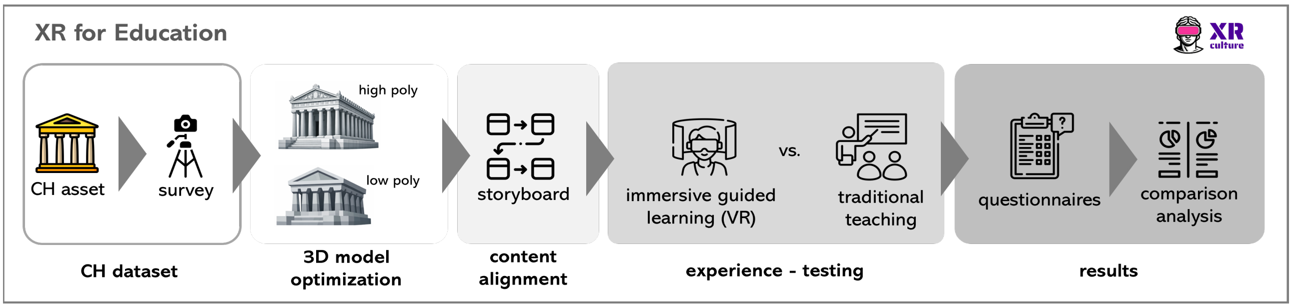

Figure 1. Methodological workflow.

choice of this monument is motivated by its architectural relevance as a representative example of Roman architecture and by its historical significance as tangible evidence of the presence and influence of the Roman Empire in the Middle East. The didactic experiment specifically aims to foster an understanding of this architectural typology, its spatial organization, and its role within the urban and cultural context of old Roman city of Palmyra. The project offers also users the opportunity to engage with CH that has been partially damaged or lost as a consequence of the Syrian civil war. In this way, the 3D recosntruction ensures continued access to collective memory while raising awareness of the importance of CH preservation.
The methodological framework builds upon the digital legacy of previous 3D reconstruction initiatives devoted to the documentation of endangered Syrian architectural heritage. The primary source data originate from the extensive work carried out by Professor Gabriele Fangi (†2020), who employed spherical photogrammetry to document (Fig. 2) and digitally reconstruct the architectural remains of Palmyra and other other at-risk Syrian archaeological and historical sites, which have been included in the UNESCO List of World Heritage in Danger since 2013 (https://whc.unesco.org/en/danger-list/). As reported in (Fangi et al., 2022), this approach enabled the production of accurate and metrically reliable 3D models even under conditions of limited physical accessibility, establishing a robust foundation for digital preservation practices.

Figure 2. Spherical panorama of the Roman Theatre of Palmyra (Syria), created by Professor Fangi (2011).

The available dataset, described in (Forte et al., 2025), consists exclusively of a source file in .blend format, namely a native file of Blender software (Fig. 3). Consequently, the initial phases of the workflow are carried out directly within this environment. Starting from this file, the first step involves cleaning the model by removing all elements not required for immersive experience, such as pre-existing lights, cameras, and animations, which are not functional for integration into the game engine. Subsequently, the model undergoes a process of mesh simplification and reduction (retopology), aimed at significantly decreasing the polygon count, from a high-poly (31,271,731 faces - 3,0 GB) to a low-poly model (653,783 faces - 66 MB), while preserving a geometric quality suitable for the architectural interpretation of the monument. Polygon reduction is therefore performed by seeking the best possible compromise between model lightness and the preservation of relevant architectural details.
Once the geometric simplification is completed, attention shifts to the reconstruction of materials and textures, a necessary step since the materials originally present in the file are not compatible with the standards required by a real-time rendering engine. For this phase, BlenderKit is used, a free and open-source add-on integrated into Blender that provides an online library of assets and PBR (Physically Based Rendering) materials. Through BlenderKit, the final materials are created based both on available library resources and on original photographs of the site, with the aim of maintaining high visual coherence and an adequate level of visual fidelity.
After completing the geometric optimization and material definition phases, the model is exported in .fbx format, preserving the subdivision into the original sub-objects rather than merging the entire structure into a single mesh. This approach allows the preservation of a modular model structure, in which architectural elements, such as the *scenae frons* with its columns and capitals, as well as portions of the *cavea*, are managed as distinct objects, thereby facilitating subsequent interaction and implementation phases.

Figure 3. 3D model of the Roman Theatre of Palmyra shown in Blender environment prior to optimization.

3.2 Storyboard definition

The design of the educational experience is grounded in the development of a structured storyboard, which represents the foundational framework for both the immersive and the non-immersive teaching modalities. The storyboard serves as a guiding tool to define the didactic content, narrative structure, and logical progression of the lesson, ensuring coherence and comparability between the two instructional approaches.
Didactic contents are defined *ad hoc* through close collaboration with high-school lecturers and art history experts, with the

aim of identifying key concepts, architectural elements, and interpretative themes that are pedagogically relevant and appropriate for both teaching formats (Fig. 4). This shared content framework ensures that the immersive and non-immersive lessons follow the same conceptual and narrative thread, differing only in the mode of presentation and interaction.

TOPIC - SCENE	VIEW - SPACE	LEARNING GOAL
Overview	360° top view of the theatre	what a Roman theatre is, origins
Case Study	Roman Theatre of Palmyra	historical & geographic context
Architecture	exploded 3D elements	identify structural and architectural parts
Construction	materials and stone blocks	building techniques
Function	*orchestra - cavea*	social and cultural role

Figure 4. Didactic contents and narrative basic structure of the storyboard for the Roman theatre lesson.

3.3 Immersive Guided Learning Experience

3.3.1 Technical aspects and hardware infrastructure. The development of the educational VR modules relies on a standardized XR stack to ensure high performance, broad hardware compatibility, and ease of deployment in a classroom setting. Specifically, the adopted stack combines the use of standalone VR technologies, selected to enable practical and immediate use in educational environments, with an OpenXR framework that allows the application to be decoupled from specific hardware platforms if needed, and a real-time development engine that brings the entire context together into a single pipeline capable of supporting both the technical and educational requirements of the experience.
A standalone VR hardware solution is adopted to support educational and training activities in virtual environments. The use of standalone VR headsets eliminates the need for external devices such as dedicated PCs, reducing logistical complexity and facilitating deployment, distribution, and management of the experience in classroom and learning settings. Among the currently available standalone VR headsets, Meta Quest 3 is selected as it is considered suitable for the development of prolonged immersive virtual experiences, thanks to a good visual resolution and an autonomy compatible with educational sessions of medium duration. However, the use of a standalone platform entails certain limitations, particularly in terms of computational power and performance, which are strongly influenced by the complexity of the 3D models employed. For this reason, mesh simplification and 3D asset optimization operations are fundamental to ensure the stability of the experience and user comfort. The choice of the Meta Quest 3 standalone hardware is also influenced by the development environment, which can currently be considered dominant for the development of VR applications.
For the final implementation of the VR experience, it is necessary to adopt a development environment capable of coherently integrating all the components of the project, including data, 3D models, design choices, and interactive content. For this purpose, a game engine is used as the central tool for assembling and managing the entire experience. Specifically, Unity is selected, as it is one of the most widely used game engines worldwide and is extensively adopted for the development of VR applications, particularly in research contexts and independent development (Carrozzino et al., 2025).
Within Unity, the previously optimized 3D model is imported and validated in relation to the adopted rendering system. To ensure stability and adequate performance on standalone hardware, the Universal Render Pipeline (URP) is used, as it is considered particularly suitable for the development of real-time VR experiences. Once the correct functioning of the model within the rendering engine is verified, the educational visrtual experience is built around it, following the design choices described in the dedicated section.
The management of navigation, interactions, and user behavior is handled through scripts developed in the Csharp programming language, together with the components provided by the game engine, which allow control over user movement, the activation of educational stations, and the logic governing the progression of the experience.
Finally, the adopted development environment allows for natural integration with the OpenXR standard enabling the application to remain compatible with different hardware platforms and supporting the replicability and portability of the VR experience.

3.3.2 Scene-based Structure. From a design perspective, the storyboard allows the VR experience to be planned in a controlled manner, managing the sequence of scenes, the overall duration, and the user's cognitive load. In particular, it defines a limited total duration of approximately 15 minutes, in order to avoid excessive information density and to ensure an adequate level of comfort for users who may not be accustomed to immersive technologies or prolonged use of VR headsets.
The experience is subdivided into distinct scenes and differentiated exploratory phases, each dedicated to specific educational objectives and content units. In this context, a scene is intended as an autonomous logical unit, designed to perform a specific function within the overall flow of the experience and to support the controlled progression of educational content, similarly to how scenes in video games correspond to different levels.
The experience is structured into three main macro-scenes, arranged in sequence, each characterized by different elements. Specifically, an initial tutorial scene, an introductory scene, and a scene dedicated to the guided experience are provided. This subdivision allows the user to be progressively accompanied from the familiarization phase with the environment and interactions, to the contextualization of the content, and finally to the guided exploration of the architectural and historical elements under study.
The functions and educational objectives associated with each scene are following outlined, highlighting their role within the overall structure of the virtual experience.

The virtual experience starts with the Tutorial Scene, as an initial phase of orientation and familiarization of the user with the immersive environment. This scene represents the first contact with the virtual environment and aims to accompany the user in the transition toward the virtual guided experience, reducing possible initial difficulties related to the use of the VR headset and interactions. Subsequently, the tutorial scene progressively introduces the main commands and interaction mechanisms, explaining how to move within the virtual environment and how to interact with the elements present in the scene. The tutorial is supported by introductory panels, visual content, and short explanatory videos that clearly and progressively illustrate how to use the commands. The narrative content is presented through multiple modalities, verbal, visual, and audio, in order to enhance accessibility and ensure an inclusive virtual experience. In particular, the integration of written text with visual elements allows users with hearing impairments to fully access the content, while audio support further enriches comprehension for a wider audience (Fig. 5).

Figure 5. The Tutorial Scene, showing the introductory panels and visual guidance provided to the user.

Once the Tutorial Scene is completed, the experience moves to the Introductory Scene characterized by a top-view perspective of an old Roman theatre, in this case placed in the archaeological area of Palmyra (Fig. 6). The user is positioned above the CH asset, offering an overall view of the architectural complex and an initial understanding of the theatre's spatial organization. After a few seconds from entering the scene, an introductory audio is triggered, accompanied by a summary textual panel, which provides an initial introduction and sets the context of the experience, in order to prepare the user for the guided path. During the introductory scene, the user's movement is intentionally limited: the user cannot move within the space but can freely orient their gaze to observe the surrounding environment. At the end of the introduction, the user can interact with the panels present in the scene to proceed to the next phase of the virtual guided experience.

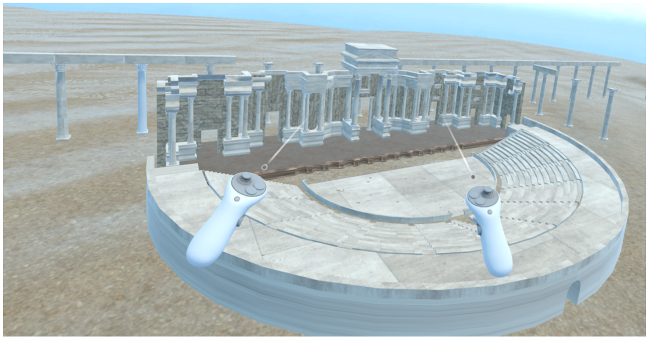

Figure 6. An overview of the Introductory Scene, showing the top-view perspective of the Roman Theatre of Palmyra.

Finally, the experience enters the Guided Station-Based Scene (Fig. 7), which represents the central part of the entire educational virtual experience. It is within this scene that the main educational activities take place, organized in the form of sequential stations, as a micro-lesson dedicated to a specific topic related to the knowledge of the Roman Theatre.

The stations are designed to be experienced in a predefined and sequential order, in order to ensure a controlled progression of the content. The user begins the educational path from the exterior of the theatre and is guided toward the first station through visual indicators highlighting the area of interest to be reached. Entering the area of interest automatically triggers the start of the lesson, while the end of the "learning pill" is signaled to the user through a dedicated message, inviting them to proceed to the next station. To avoid interruptions or situations of stalling during the experience, a fallback mechanism has been introduced: if the user does not reach the next area of interest within

Figure 7. Interior perspective of the Theatre of Palmyra from a Guided Station-Based Scene.

a predefined time interval, a warning message is displayed notifying the imminent automatic teleportation to the next station. This solution ensures the continuity of the educational experience, preventing the user from getting lost in the space or the educational experience from being interrupted.
This operational scheme is repeated for each station until the completion of the entire guided immersive educational experience. At the end the user receives a notification indicating the conclusion of the educational virtual experience. However, the experience is not immediately terminated, allowing the user, if desired, to remain within the virtual environment and freely explore it even after the lessons have ended, until the VR headset is removed.

3.3.3 Guided Learning Stations. The educational immersive guided experience is structured into four learning stations, designed as sequential micro-lessons and based on the previously defined storyboard, which establishes the educational contents explained throughout the experience.
The user begins the virtual experience outside the theatre, a design choice intended to reinforce the notion of a guided learning experience, progressively accompanying the user from the exterior toward the interior of the architectural spaces. At the start of the scene, the user is notified of the need to reach the first station, thus initiating the educational virtual experience in accordance with the planned narrative.

Station no. 1 – Historical and geographical context:
The first station is dedicated to a general introduction to the archaeological site of Palmyra. In this phase, the user receives an initial micro-lesson illustrating the historical and geographical context. In addition to the introductory audio and a summary textual panel, a geographical map is displayed, showing the localization of old city of Palmyra and highlighting its role within the Roman Empire in the Middle East, thus providing an initial historical background of the archaeological site (Fig. 8).

Station no. 2 – Structural analysis of the theater:
The second station is located inside the theater, placing the user in the middle of the *orchestra*, after crossing the threshold of the building throughout a gallery as the main entrance of the old theater. The micro-lesson focuses on the structural analysis of the Roman Theater of Palmyra, with particular attention to its main architectural components (Fig. 9). During the explanation, architectural elements are visually highlighted using distinct colors, enabling users to easily connect the verbal description with each element. At the same time, a summary panel offers brief descriptions of the analyzed elements, using the same color coding to reinforce understanding and memory.

Figure 8. Excerpt of Station no. 1 from the VR experience focused on the historical background and geographical context of old city of Palmyra.

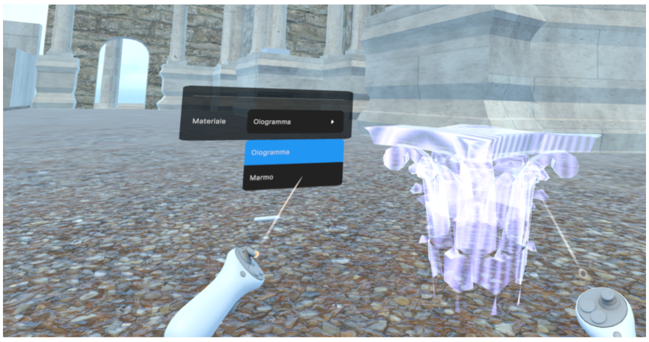

Figure 10. Excerpt of Station no. 3 from the VR experience where a capital is isolated from the structure and presented to the user to support close-range analysis and material comparison.

Figure 9. Excerpt of Station no. 2 from the VR experience showing the visual highlighting of selected structural elements of the Roman Theatre of Palmyra.

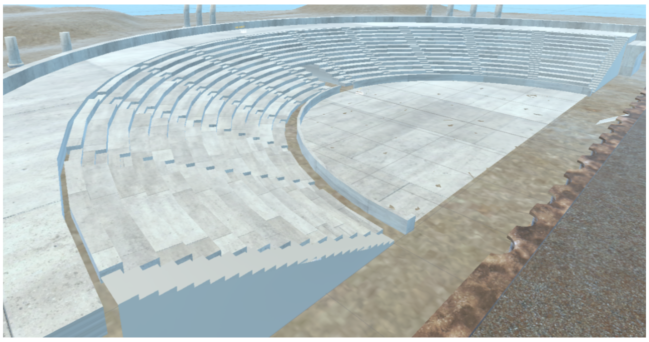

Figure 11. Excerpt of Station no. 4 from the VR experience with a view from the *cavea* of the Roman Theatre of Palmyra.

Station no. 3 – Architectural details analysis:
The third station is positioned near the stage (*scenae frons*) of the Roman Theatre and introduces a more in-depth level of analysis focused on architectural details. In this phase, a capital of the a column, belonging to the structure of the *scenae frons*, is isolated from the context and brought in front of the user, assuming an appearance similar to a hologram, in order to facilitate close observation (Fig. 10). The user can analyze the capital at close range and modify the visualization mode, switching from a stylized representation to a more realistic visualization of the original material. Also in this station, the micro-lesson is supported by audio and a summary panel, which synthesizes the main information related to the observed detail.

Station no. 4 – Role of the theatre and conclusion:
The final station is located in correspondence with the *cavea* (Fig. 11) and represents the concluding phase of the educational guided virtual experience. In this station, a final micro-lesson is proposed on the role of the Roman Theatre of Palmyra within the old city and its civil and social functions.
The lesson concludes with an overall synthesis of the addressed contents, accompanied by audio, informational panels, and ambient sounds recalling a theatrical atmosphere, contributing to reinforce engagement and to close the experience in a coherent and immersive manner.

3.3.4 User Experience Strategy. The design of the experience is guided by a user-centered approach, with the aim of accompanying the user along the educational virtual experience in a clear and progressive manner, while avoiding any perception of forced or rigid interaction. The adopted strategy seeks to achieve a balance between freedom of exploration and control of the educational flow, in order to ensure both user comfort and the continuity of the learning experience.
Movement within the virtual environment is therefore free, allowing the user to explore the space in a natural way. However, this freedom is embedded within a guided path, structured through sequential stations that define the order in which the contents are presented. If the user does not reach the next station within a predefined time interval, the system automatically intervenes through a teleportation mechanism, preventing interruptions or deadlock situations. In this way, the user remains free to move within the space, while the educational path maintains a controlled progression.
Orientation and progression management is handled through visual markers placed in the environment, designed to be clearly visible even from a distance. To reduce cognitive load and avoid confusion, only the marker associated with the currently active station is displayed, while the others remain inactive until the current "learning pill" is completed. This choice allows the user to focus attention on a single objective at a time.
Another strategical aspect of the UXD concerns the progressive distribution of information. Educational content is not presented simultaneously, but is instead divided into successive phases that accompany the user throughout the experience. The experience alternates moments of more passive engagement, based on listening and guided observation, with moments of active interaction and exploration, supporting sustained attention and reducing the risk of cognitive overload.
Finally, educational information is always anchored to the space and to the architectural elements of the virtual environment, avoiding abstract menus or interfaces detached from the context. This approach strengthens the connection between content and place, supporting a form of situated learning that leverages the immersive potential of VR to enhance understanding and content retention.

The instructional design will be developed in close collaboration with secondary school teachers from both lower and upper secondary education levels, whose involvement will support curricular alignment and pedagogical coherence. Their contribution will be essential in validating the learning objectives, adapting the content to the students' cognitive levels, and guiding the overall educational structure of the activities.

4. Preliminary Results

The preliminary results of this study derive from an alpha testing phase conducted within a comparative evaluation framework aimed at exploring the potential impact of immersive VR learning in relation to traditional, non-immersive teaching methods. Rather than drawing definitive conclusions, this initial phase was designed to identify early trends and to verify the feasibility of systematically comparing learning outcomes, usability, and user acceptance across different instructional approaches. During the alpha test, the system demonstrated its capability to support an effective data collection workflow, acting as a bridge between the immersive learning experience and online survey tools used to gather user feedback. Questionnaire responses were automatically consolidated into standardized textual and tabular formats, such as spreadsheets and form exports, enabling structured, replicable, and scalable data handling. This preliminary dataset represents the foundation for subsequent analyses and refinements in later testing phases.

From a research perspective, the alpha test primarily produced exploratory behavioral and evaluative data, which constitute the first empirical output of the project. The system was configured to collect two complementary categories of user data, psychometric and pedagogical, allowing for an initial assessment of the educational impact of the VR experience. Learning effectiveness was preliminarily explored through pre- and post-lecture knowledge assessments aimed at identifying variations in knowledge acquisition and conceptual understanding. Although the limited sample size and scope do not allow for statistically conclusive claims, early observations suggest that immersive VR-based learning may foster higher levels of engagement and perceived learning when compared to the control condition.

At this stage, the main achievement is the development of a fully operational demo that embodies the proposed approach and validates its technical and pedagogical feasibility. The demo integrates the educational stations and "learning pills" developed and reviewed in collaboration with secondary school teachers from both lower and upper secondary education levels, along with interactive functionalities and educational text and video panels. The system successfully completed an initial phase of internal technical testing, enabling early user experience and technology acceptance evaluations through standardized instruments such as the System Usability Scale (SUS) and the Technology Acceptance Model (TAM). The results provide preliminary quantitative insights into perceived usability, ease of use, perceived usefulness, and overall user acceptance, informing future iterations of the system.

Building on the outcomes of the alpha testing phase, the subsequent experimental phase will involve a sample of approximately 50 students and will adopt a comparative experimental design. Participants will be divided into two groups: a control group and a test group. The control group will attend a traditional lecture-based lesson supported by slides and direct instruction from the teacher, while the test group will engage in an immersive learning session using the developed VR application, experiencing the same educational content within a guided virtual environment. This phase aims to validate, on a larger and more representative sample, the preliminary observations emerging from the alpha test, with particular attention to learning outcomes, engagement, usability, and acceptance of immersive VR-based education.

5. Conclusions and Future Works

XR technologies are evolving at a rapid pace; however, the transfer of knowledge, skills, and design approaches from industry to education often occur with a significant delay. This gap risks slowing the preparation of future CH custodians who should be equipped with advanced tools for conservation, education, and public engagement. In this context, the present work highlights the potential of VR and 3D reconstruction as effective instruments for the enhancement, preservation, and dissemination of CH, demonstrating how immersive technologies, when informed by UXD principles, can transform digital reconstruction into accessible, inclusive, and engaging educational experiences.

The proposed methodology places UXD at the core of the learning process, ensuring that immersive environments are not merely technologically advanced but also pedagogically meaningful. Through immersive guided learning strategies, users are supported by structured narratives, contextual information, and progressive interaction mechanisms that facilitate comprehension and active engagement. The transfer of project advancements into capacity-building actions aims to support schools, educational institutions, and CH stakeholders in integrating XR technologies into curricula. By leveraging the digital library of 3D models and XR resources developed within the XR Culture project, students are enabled to explore, manipulate, and critically engage with virtual reconstructions of historical artefacts, fostering a deeper understanding of digital preservation practices and of lost or at-risk heritage.

Future developments will focus on the implementation of a didactic experimentation involving students, designed to compare traditional learning activities with immersive VR experiences developed according to immersive guided learning principles. The evaluation framework will adopt a mixed-method approach, combining quantitative and qualitative analyses to assess both cognitive outcomes and experiential dimensions. Learning effectiveness will be measured through pre- and post-intervention knowledge assessments, while usability, engagement, and acceptance will be evaluated using standardized UX instruments such as SUS and TAM.

Addressing challenges related to data accessibility, technical constraints of VR hardware, pedagogical integration, and evaluation complexity, this work proposes mitigation strategies based on data quality assurance, performance optimization, pedagogical co-design with educators, human-in-the-loop interaction models, and strict ethical compliance.

Ultimately, the XR for Education scenario within the EU project XR Culture demonstrates how UXD and immersive guided learning can contribute to the definition of best practices for XR-based education, offering a scalable and sustainable model for immersive CH dissemination that fosters inquiry, emotional engagement, collaboration, and long-term motivation.

Acknowledgements

The presented activities are developed as part of the EU project XRculture - eXplore and Reuse 3D cultural heritage within the Data Space (https://xrculture.eu/), funded under the Digital Europe Programme (DIGITAL), Call: DIGITAL-2023-CLOUD-DATA-AI-05, Topic: DIGITAL-2023-CLOUD-DATA-AI-05-CULTHERITAGE, Project number: 101174317.

References

Anwar, M. S., Yang, J., Frnda, J., Choi, A., Baghaei, N., Ali, M., 2025. Metaverse and XR for cultural heritage education: applications, standards, architecture, and technological insights for enhanced immersive experience. *Virtual Reality*, 29(2), 51. https://doi.org/10.1007/s10055-025-01126-z.

Bekele, M. K., Pierdicca, R., Frontoni, E., Malinverni, E. S., Gain, J., 2018. A survey of augmented, virtual, and mixed reality for cultural heritage. *Journal on Computing and Cultural Heritage (JOCCH)*, 11(2), 1–36. https://doi.org/10.1145/3145534.

Carrozzino, M., Caponi, M., Lanfranco, E., Giuliodori, G., Papaleo, B., Mazzei, A., Foddis, R., Bergamasco, M., 2025. Vr training for corporate first aid responders. *International Conference on Extended Reality*, Springer, 248–258. https://doi.org/10.1007/978-3-031-97766-4_19.

Dafiotis, P., Sylaiou, S., Stylianidis, E., Koukopoulos, D., Fidas, C., 2025. Evaluating Uses of XR in Fostering Art Students' Learning. *Multimodal Technologies and Interaction*, 9(4), 36. https://doi.org/10.3390/mti9040036.

Di Stefano, F., Pierdicca, R., Zaim, Z., 2022. Documentation of syrian lost heritage: 3d modelling to support an open information system and mixed reality. *Restauro Archeologico" 1972-2022 World Heritage in transition. About management, protection and sustainability."*, 2, 44–49.

Fangi, G., Wahbeh, W., Malinverni, E. S., Di Stefano, F., Pierdicca, R., 2022. Documentation of syrian lost heritage: from 3D reconstruction to open information system.

Forte, A., Alkhatib, Y. J., Bitelli, G., Malinverni, E. S., Pierdicca, R., 2025. Geomatics and metaverse for lost heritage sites documentation and dissemination: the case study of Palmyra Roman Theatre (Syria). *Virtual Archaeology Review*, 16(32), 85–99. https://doi.org10.4995/var.2024.21662.

Frontini, A., Quattrini, R., Nespeca, R., Clini, P., D'Alessio, M., Angeloni, R., Galli, I., Ferretti, U., Tangherlini, M., 2026. Dhekalos lab to metaverse: Exploring xr strategies for digital cultural heritage. *Exploring Digital Models and Immersive Spaces in Architecture and Construction*, IGI Global Scientific Publishing, 1–44. DOI: 10.4018/979-8-3373-3256-7.ch001.

Hajirasouli, A., Banihashemi, S., Kumarasuriyar, A., Talebi, S., Tabadkani, A., 2021. Virtual reality-based digitisation for endangered heritage sites: Theoretical framework and application. *Journal of Cultural Heritage*, 49, 140–151. https://doi.org/10.1016/j.culher.2021.02.005.

Hu, J., Xie, B., 2025. Design and implementation of virtual museum based on unity3d. *2025 5th International Symposium on Computer Technology and Information Science (ISCTIS)*, IEEE, 851–854. doi: 10.1109/ISCTIS65944.2025.11065447.

Innocente, C., Ulrich, L., Moos, S., Vezzetti, E., 2023. A framework study on the use of immersive XR technologies in the cultural heritage domain. *Journal of Cultural Heritage*, 62, 268–283. https://doi.org/10.1016/j.culher.2023.06.001.

Li, J., Zheng, X., Watanabe, I., Ochiai, Y., 2024. A systematic review of digital transformation technologies in museum exhibition. *Computers in Human Behavior*, 161, 108407. https://doi.org/10.1016/j.chb.2024.108407.

Liu, W., Hargood, C., Tang, W., Hulusic, V., 2025. Evaluating the impact of user and learning experience in three cultural heritage vr applications. *Proceedings of the 20th International Conference on the Foundations of Digital Games*, 1–18. https://doi.org/10.1145/3723498.372381.

Lu, J., Xiao, X., Xu, Z., Wang, C., Zhang, M., Zhou, Y., 2022. The potential of virtual tourism in the recovery of tourism industry during the COVID-19 pandemic. *Current Issues in Tourism*, 25(3), 441–457. https://doi.org/10.1080/13683500.2021.1959526.

Mitrakas, N., Tsihouridis, C., 2025. Extended reality in science learning: A comparative study of real, virtual, and mixed environments. *International Conference on Extended Reality*, Springer, 62–81. https://doi.org/10.1007/978-3-031-97769-5_5.

Nespeca, R., Quattrini, R., Ferretti, U., Giotopoulos, K., Giannoukou, I., 2023. Digital transition strategies and training programs for digital curation of museum. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, 48, 1127–1134. https://doi.org/10.5194/isprs-archives-XLVIII-M-2-2023-1127-2023.

Puggioni, M., Frontoni, E., Paolanti, M., Pierdicca, R., 2021. ScoolAR: An educational platform to improve students' learning through virtual reality. *IEEE Access*, 9, 21059–21070. doi: 10.1109/ACCESS.2021.3051275.

Quattrini, R., Pierdicca, R., Paolanti, M., Clini, P., Nespeca, R., Frontoni, E., 2020. Digital interaction with 3D archaeological artefacts: evaluating user's behaviours at different representation scales. *Digital Applications in Archaeology and Cultural Heritage*, 18, e00148. https://doi.org/10.1016/j.daach.2020.e00148.

Richter, F., Vater, J., Eger-Passos, D., Böttcher, H., Wotte, T., Jung, B., 2025. 3d digitization and immersive xr applications for paleontology education. *International Conference on Extended Reality*, Springer, 236–255. doi: 10.1007/978-3-031-97769-5_19.

Silva, M., Teixeira, L., 2021. extended reality (xr) experiences in museums for cultural heritage: A systematic review. *International conference on intelligent technologies for interactive entertainment*, Springer, 58–79. https://doi.org/10.1007/978-3-030-99188-3_5.

Stacchio, L., Balloni, E., Gorgoglione, L., Paolanti, M., Frontoni, E., Pierdicca, R., 2024. X-nr: Towards an extended reality-driven human evaluation framework for neural-rendering. *International Conference on Extended Reality*, Springer, 305–324. https://doi.org/10.1007/978-3-031-71707-9_25.