



Improving Accessibility to Cultural Heritage: Integration of Extended Reality, Tactile Prints and User Experience Analysis for the Church of Madonna dell'Itri

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The theme of accessibility is one of the most delicate aspects within the cultural heritage domain and can be approached in various dimensions, encompassing not only physical accessibility but also sensory and cognitive accessibility. This article presents the outcomes of the implementation of the 'Intra l'Itri' project, aimed to enhance the accessibility of the church of Madonna dell'Itri in Nociglia, Italy, using eXtended Reality (XR) technologies. The church harbours an ancient pictorial palimpsest with layers of historical significance, compounded by structural alterations over time. Funded by the Salento Interprovincial University Consortium (Consorzio Universitario Interprovinciale Salentino - CUIS 2020), the project engaged interdisciplinary collaboration involving the University of Salento's Department of Engineering for Innovation and Department of Cultural Heritage, the Municipality of Nociglia, local companies, associations and professionals. Its objectives encompassed studying and conserving frescoes and the church's structure, facilitating intelligent cultural immersion, enhancing visitor

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accessibility and fostering local identity. This contribution focuses on the developments of Augmented Reality (AR) and Virtual Reality (VR) applications, digital restoration visualisation, as well as 3D and tactile prints. It presents results and findings from the test campaign, validating the digital strategy aimed to enrich the accessibility of this historically significant artistic site.

CCS Concepts: • **Computing methodologies** → **Virtual reality; Mixed / augmented reality**; • **Human-centered computing** → **Usability testing; Accessibility technologies; Virtual reality; Mixed / augmented reality**;

Additional Key Words and Phrases: Accessibility, Cultural Heritage Enhancement, Virtual Reality, Augmented Reality, 3D prints, Tactile prints, User Experience

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1 Introduction to ‘Intra l’Itri’ Project

1.1 Premises

In the domain of cultural heritage, accessibility refers to the range of practices, tools and policies aimed to ensure that cultural sites, institutions and resources are accessible to all individuals, regardless of their physical, sensory, cognitive, or social abilities. This concept is not limited to physical access alone but extends to intellectual and social accessibility, ensuring an inclusive approach that promotes active participation and enjoyment by a diverse public.

According to the **International Council of Museums (ICOM)**, access to cultural heritage is a fundamental right. ICOM emphasises that museums and cultural institutions should embrace inclusivity in their policies, facilitating a visitor experience that is welcoming and engaging for all audiences. This aligns with ICOM’s broader commitment to fostering equality and inclusion in cultural spaces. The ICOM Code of Ethics explicitly promotes accessibility, encouraging museums to eliminate physical, sensory and intellectual barriers that might hinder individuals from fully experiencing heritage resources.

For audiences with disabilities, specific requirements must be addressed to achieve meaningful access. For instance, people with physical disabilities may require ramps, elevators and adaptable seating arrangements. For individuals with sensory impairments, such as visual or auditory disabilities, museums might offer tactile exhibits, audio descriptions, sign language interpretation and closed captions. Cognitive accessibility is also essential, requiring simplified signage, clear information displays and structured navigation paths that cater to people with cognitive or learning disabilities.

Furthermore, the emphasis on universal design creating environments usable by all people without the need for adaptation has become a critical aspect of accessibility in cultural institutions. This approach not only benefits individuals with disabilities but enhances the overall experience for all visitors. The theme of accessibility is one of the most delicate aspects within the cultural heritage domain and can be approached in various dimensions, encompassing not only physical accessibility but also economic, sensory and cognitive accessibility.

In Italy, the Directorate-General for Museums (Direzione Generale Musei) has detailed the objectives and standards to which museums must adhere in terms of accessibility [19]. A crucial point is to avoid differentiated paths based on the type of disability since the museum experience is also about sharing. While leaving the visitors the freedom to consciously and autonomously build their own cultural and emotional experience, museum professionals should provide the opportunity of mediation inside and outside of the experience.

This includes grading the complexity of interpreting heritage from a simplified level suitable for an audience with basic literacy or cognitive deficits, enhancing multisensory perceptions through the identification of several itineraries that can involve visual, tactile, auditory, olfactory and gustatory perception, and allowing for managing visit times considering both audience needs and the safety.

The digital revolution witnessed in recent decades has completely changed the paradigms of perception and enjoyment of cultural heritage. Technologies such as **eXtended Reality (XR)** are increasingly spreading in contexts such as museums, galleries and archaeological sites, to the extent that visitors are learning to use these new tools according to their needs. Furthermore, a multidisciplinary approach is necessary to design and develop technological solutions that take into account specific requirements for the enjoyment and narration of cultural heritage, as described in this contribution. This is not a loss of authenticity but rather an enrichment for each discipline that can multiply its potential. The process outlining the forms and methodologies underlying this new approach to cultural heritage is known as digital transformation.

The need to start a digital transformation process in the cultural heritage area can be traced back several decades. In fact, European Commission policies¹ have explicitly emphasised the need to democratise resources of universal value through digitisation, accessibility and interoperability. XR, which includes **Virtual Reality (VR)**, **Augmented Reality (AR)** and **Mixed Reality (MR)**, has significant potential to enhance the accessibility of cultural heritage sites by creating immersive, interactive experiences that can accommodate diverse needs. VR technologies can restore the sense of presence, simulate environments, artefacts and stories, enabling visitors with mobility, sensory, or cognitive impairments to experience cultural assets in ways that were previously challenging or inaccessible. Additionally, tactile technologies, **Near Field Communication (NFC)** systems, Braille text prints and audio descriptions offer targeted solutions for various accessibility needs, providing information through touch, sound, or close-range digital interaction.

However, the challenge arises in integrating these technologies into a coherent, universally accessible experience that respects the principles of universal design. The goal is not merely to adapt spaces or exhibitions for specific groups but to foster inclusive environments where experiences are shared and accessible to all visitors without exclusion forms. This requires careful consideration of diverse visitor needs, balancing specific accessibility features with the overarching goal of creating a seamless, unified visitor experience.

1.2 Goal of the Contribution

This work presents the results of the implementation of a project called ‘Intra l’Itri’. The project aimed to improve and develop the accessibility of the Madonna dell’Itri Church in Nociglia, Italy, by means of XR technologies.

The church features a very ancient pictorial palimpsest, with early layers being illegible or extremely incomplete, as well as multiple structural alterations attesting to the varied historical events to which the church has been subjected.

The project aimed to study and monitor the conservation status of the frescoes and the structure of the church, improve the enjoyment of the cultural asset, improve accessibility in terms of the visitor experience and promote local identity through outreach activities. A previous article [22] described the design and a first implementation of the different applications for the digital setup. This article focuses on the final development of AR and VR applications, as well as the 3D and tactile print, and it discusses the results collected through a test campaign, conducted to validate the digital strategy that, through the use of XR and tactile apparatus, was designed to improve the accessibility of this important historical and artistic site. The research investigated whether these technologies, combined with digital restoration techniques and tactile elements, can provide a more inclusive, accessible and immersive experience for visitors. Additionally, the research questions focus on how such digital strategies can facilitate the exploration and dissemination of cultural heritage in historically significant yet

¹Framework Convention on the Value of Cultural Heritage for Society. In Faro Declaration of the Council of Europe’s Strategy for Developing Intercultural Dialogue; Council of Europe: Strasbourg, France, 2005.

geographically isolated, peripheral or decentralised sites, such as the church in Nociglia. The study also examines how these innovations contribute to the preservation and interpretation of complex historical narratives while fostering a stronger sense of local identity and connection to cultural heritage. Therefore, questions that drove this research can be summarised as follows:

- Q1: Can XR technologies, specifically AR and VR, be utilised to enhance physical, sensory and cognitive accessibility at cultural heritage sites for diverse visitor groups, including those with disabilities?
- Q2: Can the integration of XR technologies, digital restoration and tactile elements offer a more inclusive and informative exploration experience for visitors, while preserving and interpreting the complex historical layers of a site like the church in Nociglia?
- Q3: Can the use of digital strategies, particularly in peripheral and isolated historical and artistic contexts, support not only the accessibility of the site but also its dissemination, thus strengthening the connection between the local community and their cultural heritage?

1.3 Structure of the Contribution

After the introduction, this work has been organised as follows:

- Section 2 explores the current accessibility landscape, focusing in particular on the intersection between XR technologies and cultural heritage;
- Section 3 examines the case study of the church of Madonna dell'Itri in Nociglia, providing a description of the monument and a brief examination of the specific challenges encountered in terms of accessibility and enjoyment;
- Section 4 analyses the research design and the development of the visitor experience, divided into three subsections: AR Application, VR Application and Tactile Equipment. Each subsection explores the design principles and technical aspects involved in the development of these accessibility solutions, offering insights into their implementation and potential impact on enhancing the visitor experience;
- Section 5 presents tests and results to evaluate the effectiveness and usability of the implemented accessibility solutions. It includes user feedback and observations derived from testing sessions with diverse user groups;
- Section 6 discusses the implications arising from the analysis of the data collected in the experiment;
- Lastly, Conclusions and future work discuss results and perspective research in the realm of the project.

2 Accessibility Challenges: A Brief State of the Art of XR and Cultural Heritage

Accessibility remains a critical challenge in many cultural heritage sites worldwide. A study on Petra, Jordan's World Heritage Site, highlights how significant physical, financial and cultural barriers can limit visitors' experiences [1]. The site's difficult terrain, lack of adequate infrastructure, high entry costs and limited interpretative materials hinder access, particularly for individuals with disabilities, elderly visitors and low-income tourists. While some management efforts have been made, a comprehensive strategy is still needed to balance site conservation with inclusivity, ensuring equitable access to its historical and cultural significance.

In response to these challenges, the digitisation of cultural heritage emerges as one of the increasingly adopted tools by museums and institutions to enhance accessibility to historical and artistic assets [6]. This approach, besides allowing a broader audience to explore and understand heritage without geographical or temporal limitations, also facilitates access for individuals with diverse abilities, promoting a more democratic and inclusive cultural experience [18].

In this perspective, emerging technologies play a fundamental role in promoting inclusivity in the cultural heritage area. XR stands out as a resource of great importance for cultural heritage enjoyment, introducing an innovative paradigm of interaction with history and art. Through the integration of technologies such as VR and AR, the exploration experience of cultural heritage transforms into an engaging immersive journey through time

and space [23]. A novelty in the field of MR is represented by the use of Virtual Portals, a technological means that allows crossing the boundary between the real and virtual worlds [16].

Digitised historical and artistic assets can also be experienced through 3D printing, a process that involves creating detailed and faithful replicas of artworks and archaeological artefacts. This practice fits into the broader context of democratising access to cultural heritage, opening up new opportunities for exploration and appreciation of history and art by users from diverse backgrounds and with various abilities [10]. 3D printing not only enables accurate reproduction of historical artefacts but also represents an innovative means to make such replicas accessible to a wider audience, including those who may be physically distant from the locations where these works are preserved [26] or who have visual impairments.

Closely correlated with technologies like XR and 3D printing, the concept of virtual restoration can be described as the application of ‘a series of integrated computer graphics approaches, both two and three-dimensional, aimed to restore an archaeological, architectural, or artistic object to its original integrity, or at least nearly complete’ [30]. This practice is characterised by its multidisciplinary nature, requiring expertise from fields such as conservation, art history, archaeology, traditional restoration, computer science and physical and chemical sciences [34].

Virtual restoration of frescoes represents an advanced approach in preserving and recovering artworks of historical and cultural value. Through the use of technologies, experts can digitally recreate damaged or degraded mural paintings over time. This process allows for the virtual reconstruction of the original figurative and chromatic elements, preserving the artistic and historical richness of the work. This methodology is particularly useful when facing challenges such as partial or total loss of frescoes due to catastrophic events or natural degradation. Compared to real restoration, the virtual approach has the advantage of operating on ‘cloned’ works, and therefore, since these can be modified, duplicated and restored, it offers greater freedom of intervention, allowing for the formulation of different hypotheses and ease of making subsequent changes [4]. However, it is important to note that every intervention, even if carried out in a virtual environment, should respect the fundamental principles of reversibility, compatibility, minimum intervention and recognisability, as outlined by Cesare Brandi in his *Theory of Restoration (Teoria del Restauro)* [8].

An example of virtual restoration that followed the principles of real restoration was the one that involved the southern wall of the cave church of the Original Sin in Matera. Using photo-modelling and direct photographic surveying, various forms of degradation were addressed, including gaps and losses of paint film. The digital recovery process improved the readability of the work, allowing simulations on the perception of lights and colours in the cave church. The use of white colour in the background of the fresco proved to have a practical role in illuminating the cave environment [31].

Within the realm of virtual restoration operations, one of the most commonly adopted practices is anastylosis, a restoration technique primarily used in archaeology and architecture to reconstruct ancient buildings or monuments, using the original fragments that still exist. Essentially, it involves reassembling a collapsed or deteriorated structure by putting together its original parts, when possible, and integrating the missing portions with materials that are recognisable as modern. For the intervention to be accurate, the repair of missing parts must be based on the concepts of style and analogy [38].

Among the early experiments in computerised anastylosis, particular mention deserves to be made of that concerning the frescoes of the Ovetari Chapel in the church of the Eremitani in Padua, damaged during the bombing of 11 March 1944. The project, named ‘Mantegna’, allowed for the reassembly of some pictorial fragments through the use of innovative algorithms [46].

Virtual restoration of painted surfaces can be simulated through the use of wearable devices such as Microsoft HoloLens or mobile devices like smartphones and tablets. Alternatively, a specific technology known as projection mapping can be applied. In the first case, the overlay occurs through technologies like MR or AR, which essentially superimpose virtual elements onto the real environment. An example of chromatic recovery using AR of parts of

lost frescoes is represented by the case of the wall paintings of the Basilica of Saint Caterina d'Alessandria in Galatina (Italy) [15].

The technique of projection mapping has been applied to the Crucifixion of Christ, a work from 1350 housed in the Museum of Casa Romei in Ferrara, previously detached from the church of Saint Caterina in 1935. In the context of the 'Sogno o Son Deste' project, surveys, photographs and historical documents are used to reassemble the entire original pictorial cycle of the church. The methodology includes high-resolution photographic shots, colour profiling and chromatic comparison between the frescoes. Specific challenges related to projection are addressed, such as managing the background colour and lighting. Despite difficulties in colour control during projection, the project has significantly contributed to improving the understanding and accessibility of the work, fostering cultural and perceptual inclusion [24].

In recent times, virtual restoration increasingly relies on advanced technologies based on deep learning for the reconstruction of missing parts and the correction of cracks. The latest research demonstrates how sophisticated AI algorithms enable intervention on the inevitable signs of aging, recognising and correcting them virtually [21, 45].

An innovative virtual-real fusion approach based on AR for fresco restoration is illustrated in a recent study aimed at overcoming the limitations of isolated virtual reconstructions. This approach promotes a semantic association between virtual frescoes and the physical environment, employing a mechanism of visual attention and real-time mapping of the physical environment with integrated restoration information [48].

In the realm of art accessibility for visually impaired people, an important solution for making artworks more inclusive is the interactive multimodal guide described in [40]: it allows triggering localised verbal, audio, wind and light/heat feedback events that convey spatial and semantic information when a 2.5D representation of a painting is touched. A system to assist people with visual impairments in the tactile exploration of bas-reliefs was implemented using hand tracking [11]. Moreover, several methods have been developed to represent colours for people with visual impairments using multisensory approaches:

- *Thermal Interaction*: The method proposed in [3] exploits warm and cold temperatures to represent depth and colour temperature;
- *Sound Colour Coding*: The interactive multimodal guide introduced in [39] uses audio and tactile modalities to improve the autonomous access to information and experience of visual artworks; additionally, a 3D sound colour coding was defined [27], where the colour hue is represented by the sound simulation of the position of the colour wheel and the lightness of the colour is reflected by using the pitch of the sound;
- *Wearable Tactile Technology*: The ColorWatch device [25] was designed to map colours to tactile spatial positions;
- *Multisensory Colour Coding*: System was described in [14] that integrates patterns, temperatures, scents, music and vibrations to provide a richer colour perception experience; similarly, the colour representation system described in [41] uses sounds and scents to represent up to 30 colours.

3 Case Study: The Church of Madonna Dell'Itri in Nociglia

The church of Saint Maria de Itri, located just outside the historic centre of Nociglia and now fully integrated into the urban area, has likely served as a natural stopover for pilgrims heading to the ancient sanctuary of Santa Maria de Finibus Terrae over the centuries, especially in the late Middle Ages, thus leaving a significant mark on the history and culture of Puglia. The church name, dedicated to Madonna dell'Itri, originates from the Byzantine cult of Madonna Odigitria, whose meaning of 'she who leads, showing the way' has evolved over time into Idria, Itria, or Itri, undergoing various linguistic and semantic changes for ease of pronunciation.

Built in the second half of the 11th century, during the final years of Byzantine rule, the church is now completely incorporated into the 18th-century structure and has an opening in the floor that leads down to a crypt with an ossuary. The original structure of the church, characterised by a rectangular floor plan and a gabled

roof supported by wooden beams, measures approximately 12 metres in length along the East-West axis and 6 metres in width along the North-South axis, with a maximum height of 7 metres. The nave terminates to the east with the apse arch, currently devoid of its external extension, which likely collapsed or was removed at an unspecified time. Near its end, a small rectangular niche likely served as a sacristy, while illumination was probably provided by a small window on the southern wall. In addition to the main entrance on the western wall, another door, now bricked up, served as a secondary entrance facing towards the castle and the village.

The decorative program of the church exhibits a clear historical stratification in the frescoes on the walls, dating from the 11th to the 16th century, albeit made difficult to interpret due to overlapping layers over the centuries. The analysis of the decorative program and its stratigraphy, that is the superimposed layers of pictorial materials, reveals five overlapping painting phases dating from the 11th to the 15th century, reflecting cultural influences and changes in taste, with one phase attributed to a Salento painter from the 15th century. The original structure of the church underwent various changes over time, as evidenced by restoration interventions up to the significant work carried out in 1982, which allowed for the recovery of frescoes and sculptures. Today, access to the church is through another building, an 18th-century-style church, despite being completed in 1921 [37].

4 Research Design and Development of the Visitor Experience

The research design of the ‘Intra l’Itri’ project follows a mixed-methods approach, structured in three phases to address both qualitative and quantitative research questions on accessibility, user experience and local engagement in cultural heritage. The first phase consisted of a preliminary needs assessment of the church in Nociglia, engaging local stakeholders and experts to identify accessibility and preservation challenges. In the second phase, artefacts digitisation, digital restoration and XR applications development were performed to address these needs by offering immersive, multisensory experiences. Complementary 3D-printed tactile elements were created to transform the visitor experience into an interactive, tangible engagement. In the final phase, a usability study gathered feedback from 30 participants, using the **System Usability Scale (SUS)**, the **Short User Experience Questionnaire (Short UEQ)** and custom questions. This test was used to evaluate the effectiveness of the methodology and the efficacy of the integration of these technologies, in enhancing accessibility, usability and local community connection to the cultural site.

Specifically, two applications have been developed, one of which is an AR application, focusing mainly on the church’s pictorial palimpsest and on its temporal evolution, and a VR application that completed the AR one by also visualising the building’s architectural evolution. Finally, 3D printing technology met the needs of accessibility by transforming the experience from intangible to tangible.

Each solution has been designed according to the accessibility standards, provided by the guidelines published by Directorate-General for Museums (Direzione Generale Musei) of the Italian Ministry of Culture [12]. The project addressed accessibility issues for people with visual impairments from the early stages of design and implementation through to deployment, collaborating with the **Italian Typhlotechnical Centre (ITC)** of Lecce. The centre’s staff, composed of both sighted and blind experts in visual accessibility, carried out an ongoing evaluation of all developed applications to ensure their usability for users with visual impairments. The solutions implemented were designed based on the specific requirements provided by the ITC.

The adopted approach focuses on the seamless integration of digital and tactile content to create an inclusive and accessible experience for all users, including people who are blind and people with visual impairments. By combining AR and VR technologies with tactile and audio-based solutions, cultural heritage can be experienced through multiple sensory channels. In the AR application, visual content is complemented by NFC-tags with tactile reliefs, allowing users with visual impairments to navigate the space independently and access audio descriptions. This integration ensures that digital enhancements do not exclude those with visual impairments but instead provide alternative means of interaction. Similarly, in the VR environment, 3D spatial audio guides users through the experience, making the virtual space perceivable without relying on sight. To further support

accessibility, each fresco described in the app audio guide is also reproduced in a tactile catalogue. This allows users to explore the artwork through touch, reconstructing an accurate mental image of both the preserved details and missing sections. The combination of digital elements, spatial audio and tactile equipment, creates a fully integrated and inclusive experience, ensuring that cultural content is accessible and meaningful for everyone, regardless of sensory abilities.

Another strategic topic is the virtual restoration: it was conceived to be the conceptual starting point of the AR and VR application. The first stage of the work was the study of the intricate decorative palimpsest of the walls and the identification of some frescoes of interest. Thanks to virtual restoration it is possible to evaluate whether and how to intervene on the art-work without affecting it in any way, thus preserving its current state. The frescoes selected for the digital restoration are eight: for the Western Wall 'Parasceve (or Paraskeva) Virgin', for the Northern Wall 'Praying Madonna and Child', 'Saint Nicholas', 'Madonna of the Veil' and 'The Holy Face (Mandylion)'; for the Southern Wall 'Saint Anthony Abbot (or Anthony the Great)', 'The Archangel' and 'Saint Cesarea'. The AR application allows the user to scan the fresco of the walls from a certain distance, to explore through a slider its transformations over time (before and after physical restoration) and to compare it with the outlines and colours of the virtual restoration. In addition, this catalogue of images is enriched by more detailed description sheets for each fresco, also reproduced in audio tracks for easier accessibility.

On the other hand, the VR application enhance the accessibility and the immersiveness, allowing the users to immerse themselves in the architectural transformations of the church, with two different levels of participation: on the one side a more active experience, in which the user autonomously chooses where to move and what to view; on the other side a guided tour, which requires less interaction from the user, designed also to meet the needs of users with physical disabilities.

Finally, the technology of 3D printing and of NFC-tags made it possible to 'translate' the two applications into a tactile setup.

In particular, the 3D model of the church and the sculptural apparatus (altar and statues of Saint Peter and Saint Paul) was first recreated in 3D, through the technique of photogrammetry, and then printed in 1:8 scale.

To complete the model, two tactile panels were installed, in which the user can touch the outline of the church in plan and the altar, raised on the panel, and the relative description also translated into Braille. Moreover, thanks to the NFC-tags and QR codes on both panels, the audio content can be accessed, extending the enjoyment also to users with visual impairments.

Following the guidelines of the panels, the tactile catalogue, created with the aid of a specific technology (see Section 4.3), reproduced part of the wall paintings of the church of Itri on paper with raised line drawings.

A map of the church, indicating the location of the tactile equipment, VR stations and AR points of interest, is shown in Figure 1.

Inside the church, both the visors (Meta Quest 2) and the tablet (Galaxy Tab Active 3 LTE Enterprise Edition) are available for VR and AR applications, respectively. The first was chosen for its versatility as a standalone visor that provides excellent immersion; the second was selected for its compatibility with AR technology and NFC-tags. This digital setup, already in place, facilitates visitor access to content, meeting accessibility standards and aiding in the acquisition of information about the site.

In conclusion, in the design phase of the user experience, each of the above-mentioned technologies was imagined to be complementary to the other, in order to meet the main objectives of the project: enhancing the church in Nociglia with its pictorial and sculptural apparatus, and promoting its knowledge to a target as heterogeneous as possible.

4.1 AR Application

The application, divided into two distinct sections, has been developed using Unity3D, AR Foundation 4.2.7 and NFC Plugin 5.1.1, leveraging AR technology to offer a dynamic and interactive experience. The first section,

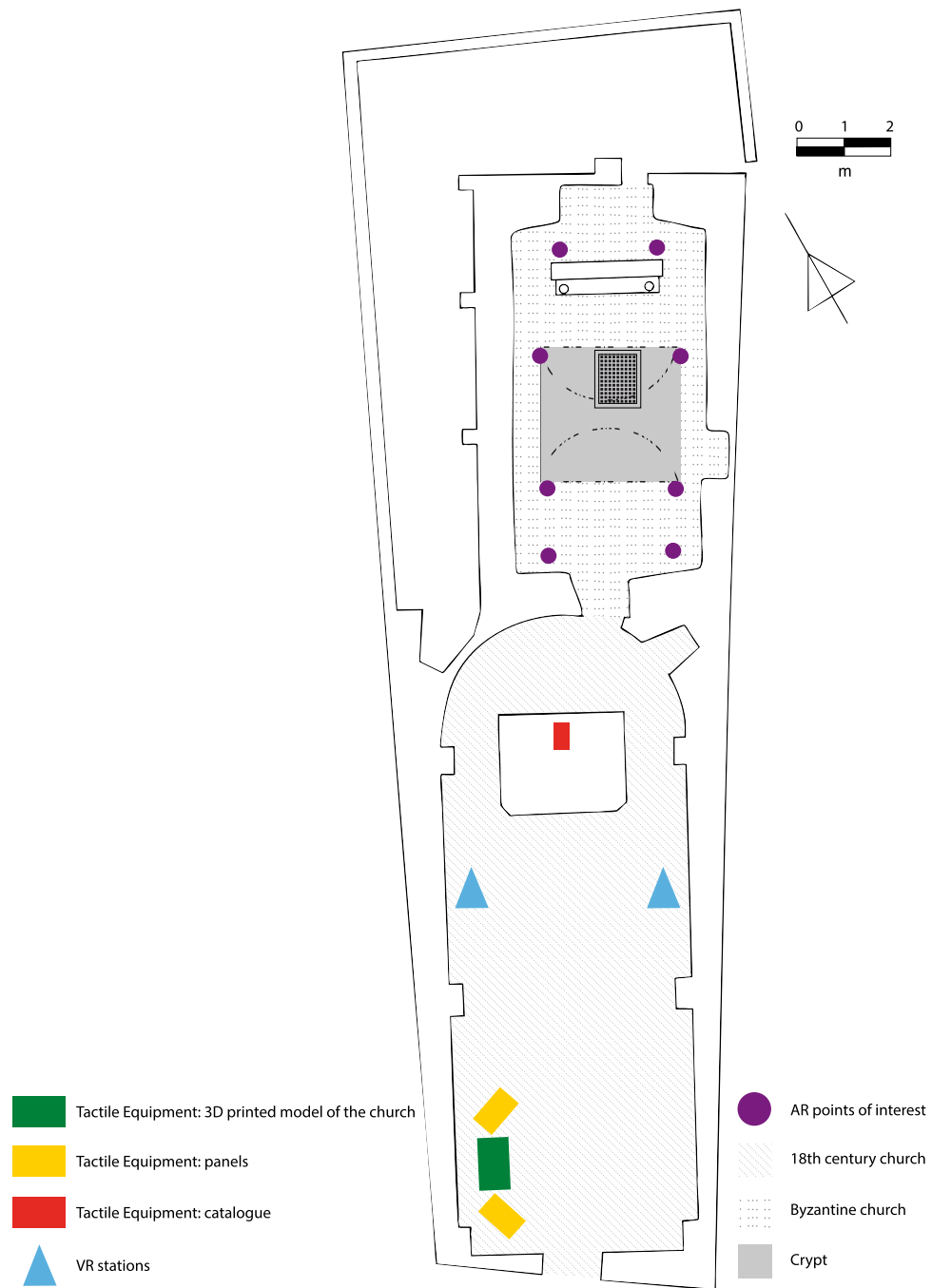


Fig. 1. Floor plan of the Church of Madonna dell'Itri, showing the 18th-century structure, the Byzantine church, the crypt and the locations of Tactile Equipment, VR stations and AR points of interest.



Fig. 2. AR application showing frescos in four layers: before the restoration, after the restoration, layout and digital restoration.

accessible exclusively within the church, allows users to digitally explore the frescoes by framing a portion of them with the provided tablet. Following this action, the system automatically overlays various pieces of information onto the real image of the fresco, organised into multiple viewable layers that can be explored individually (Figure 2).

The available information layers include four types:

- *Pre-Restoration Photos*: These images allow the user to observe how the artwork has evolved over time, showing how environmental changes and restorations have influenced its preservation.
- *Post-Restoration Photos*.
- *Digital Reconstruction of the Figure*: This is a digital outline of the original image, meticulously reconstructed to highlight iconographic details that may otherwise be difficult to discern in the real artwork. This layer allows users to appreciate elements essential to a full understanding of the fresco and its symbolism.
- *Digital Restoration of the Painted Layer*: This virtual version of the fresco restores the original colours, digitally recreating deteriorated or faded sections. This layer provides a vivid and realistic representation of how the fresco originally appeared, allowing for a deeper immersion in the artistic experience.

A key feature of the application is the side slider that enables a smooth transition between different informational layers. The slider, located on the right side of the screen, allows the opacity of each layer to be adjusted by modifying the alpha values. When the user moves the slider, the image of the current layer gradually fades, making way for the next layer (Figure 3). This feature promotes a dynamic and interactive exploration of the fresco, offering unique perspectives and details that may otherwise be hard to capture with the naked eye and fostering a more complete and immersive understanding of both the artwork and its history.

The points of interest, associated with the frescoes that have undergone virtual restoration, are marked with placeholders indicating where the user should stand to correctly frame portions of the fresco. The virtual restoration, carried out in collaboration with art historians who provided detailed iconographic guidance, was manually executed using a Wacom graphic tablet and Adobe Photoshop software. During this process, visible



Fig. 3. Use of the AR application.

details were enhanced to facilitate the reading and understanding of the fresco, thus enhancing its iconographic complexity.

The second section, accessible even outside the church, does not employ AR. It allows users to access a range of historical and artistic information related to the building and its frescoes, as well as the option to listen to audio tracks with relevant descriptions. These tracks, varying in length (from approximately 30 seconds to 2 minutes), describe the church's key features and artistic elements and can be accessed by approaching NFC-tags and scanning QR codes placed on tactile panels (see Section 4.3).

Particular attention has been paid to accessibility for people with visual impairments, designing a simple UI that ensures easy and intuitive access to audio content. These enhancements foster greater inclusivity, making the experience accessible to a wider audience and offering an in-depth understanding of the artworks and their history. Since AR is primarily a visual experience, users with visual impairments would typically be excluded from its content. However, the use of NFC-tags makes the application accessible to them as well. By touching or scanning the NFC-tags, which are marked with a raised tactile icon on the panels, users can move through the space independently and access audio descriptions of the artworks. This system ensures that they can engage with the same cultural content as users who are sighted, through an alternative sensory modality. Furthermore, every fresco described in the app's audio guide is also reproduced in a tactile catalogue. This allows users with visual impairments to explore the shapes and details of the frescoes through touch. As a result, they can build an accurate mental representation of each artwork, including its preserved sections as well as any missing or deteriorated areas, and its exact collocation in the church space. This multisensory approach enhances the accessibility of cultural heritage, making it possible for individuals with visual impairments to fully appreciate the artistic and historical value of the frescoes.

4.2 VR Application

The second application, based on VR technology, offers an immersive virtual tour experience of the church. Using a VR headset like the Meta Quest 2, users can explore a photogrammetric reconstruction of the church. Before developing the VR application, the 3D model of the church was created by photogrammetry. Specifically, a photo

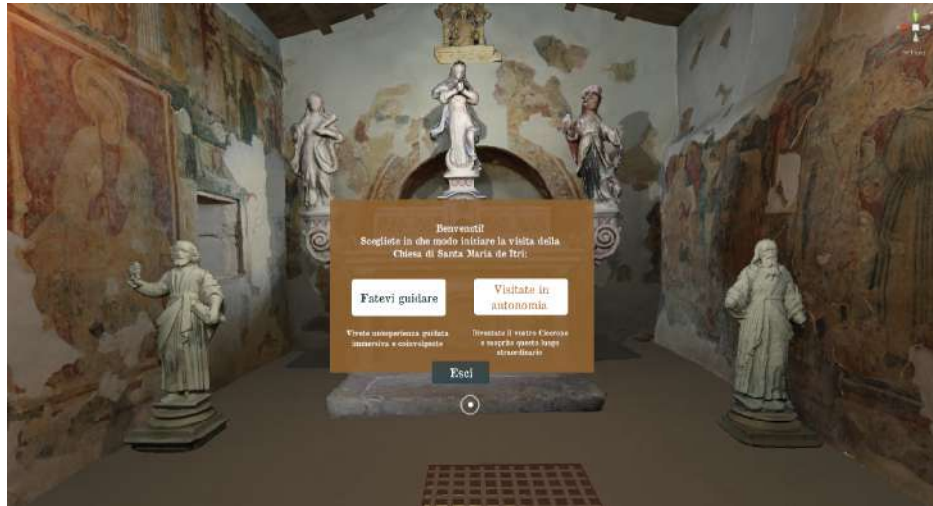


Fig. 4. VR environment of the inside of the church, with the menu buttons for choosing between self or guided tour.

campaign was conducted by capturing about 550 photos, with a camera Nikon D3200 (18-55), using a fixed zoom lens, and with the help of a scaffold to lift the operator off the ground and capture detailed photos of even the tallest sections. After acquisition, the photos were processed in AgiSoft Metashape obtaining a model of around 220.000 polygons. Then Blender software was used to clean and optimise the model, perfectly closing the open geometries and reconstructing the missing parts (such as the reconstructive hypothesis of the ancient apse with double lancet window). The 3D modelling has been used also for creating and texturing the floor and the wooden roof of the church, since now these parts are fully modern and they are not historically relevant. This is also a good way for optimising and reducing the number of polygons.

The photogrammetry process was performed separately for the altar and statues. For the development of this app, Unity3D was employed, while XR Interaction Toolkit 2.3.2 and XR Plugin Management 4.2.0 were utilised to handle VR functionalities.

Through the use of Unity XR Interaction Toolkit, it became possible to implement interactions within the virtual environment. In particular the application makes use of the Gaze Interactor. This mechanism is based on raycast tracking, which allows the user to interact with visual elements simply by looking at them, without the need to use controllers. Through the Gaze Interactor, users can direct their gaze to a button to activate it and access-related information. This camera direction-based interaction method provides an intuitive and accessible experience without using controllers. At the beginning of the experience, the user can choose between two modes of exploration: autonomous versus guided tour (Figure 4). In the autonomous exploration, the user explores the environment freely, without following an order of observation, by means of nine teleportation points, in the shape of footprints placed along the virtual floor. By interacting with these points, a teleport mechanism is activated. One point of interest leads to the spherical photo of the crypt below the church, which was captured using the Ricoh Theta 360°. In the guided tour mode, instead the user is in the centre of the virtual room, without acting any teleportation. Specifically, it is the lighting that guides the user's gaze, as virtual spot lights turn on and off according to what the guider's voice tells the user, so as to indicate to the user where to turn the gaze.

Furthermore, to facilitate a better understanding of the construction phases of the architecture, users have the option to 'go back in time' and view the church in its original form, devoid of modern additions such as the altar and the statues. The 3D model of the past is the same of the present, but when the user choose to go in the past scenario, some elements are disabled since they were not in the church at that time, such as the altar and the



Fig. 5. VR environment with the virtual restoration of ‘Saint Cesarea’ overlaid onto the actual fresco.

statues, and some other are activated, such as the apse with double lancet window. While navigating the building, the user can interact with buttons represented by meaningful icons and located at some points on the walls. These buttons provide access to several kinds of content about the frescoes cycles: texts about the history, audio-guide description, comparison pictures and photos from the past. A special button is dedicated to the virtual restoration of the wall frescoes: users can compare the image of the preset to the hypothesis of the original outlines and colours of the fresco, thanks to the virtual restoration (Figure 5). In the VR experience, 3D spatial audio has been integrated as a way to support users with visual impairments in orienting themselves and engaging with the virtual space through sound cues. While this approach can enhance accessibility by providing an alternative sensory reference, it is not a universal solution, as the effectiveness of audio-based navigation varies depending on individual abilities and preferences. This approach offers an immersive learning experience, allowing users to learn about the history and importance of the building.

4.3 Tactile Equipment

In order to make the church of Madonna dell’Itri accessible from multiple perspectives and for all types of users, the experience design included the creation of tactile equipment consisting of two panels, a catalogue and a 1:8 scale 3D model of the church placed directly *in situ*.

This choice, in line with what is explained in the *Enhancement Notebooks. Accessibility and Cultural Heritage (Quaderni della valorizzazione. Accessibilità e Patrimonio Culturale)*, highlights the necessity, as well as the commitment, to embrace the inclusiveness as a foundational element of a democratic and horizontal culture. Providing all visitors with access to cultural sites and the information related to them creates not only involvement, but also community awareness and memory, which become care for a heritage to be preserved and transmitted.

To this end, two tactile panels were initially designed for the church, featuring raised line drawings and Braille text (Figure 6). The first panel provides information about the structure’s characteristics, describing its history and architecture. On it, the raised lines of the church’s plan allow visitors to understand its features and environments. The second panel focuses on the 17th-century Baroque altar located in the ancient Byzantine church, showcasing



Fig. 6. Tactile panels inside the church. In particular, the picture shows, in an exemplary manner, the second panel focused on the altar, with all tactile raised lines and Braille text highlighted in red.

raised line drawings of this altar. Both panels are positioned and mounted inside the church (thanks to the supports made by the company TR Inox) at accessible heights [36] (e.g., children, adults in wheelchairs, or standing users), enabling tactile exploration of key elements. This solution primarily meets the needs of people who are blind or visually impaired, but it also provides useful information for all visitors. Additionally, users can access audio content via the AR application (for more on this, see Section 4.1): a QR code and an NFC-tag are also marked with raised lines and located in the lower right part of the panels, allowing users to activate informative and descriptive audio guides for an enriched sensory experience. Users can access the audio guides by either scanning the QR code with the camera of the provided tablet or by bringing it close to the NFC-tag.

Both panels, printed by the Stamperia Regionale Braille of Catania (Italy), follow the guidelines [28] on font type and size, line spacing and graphic design useful for the realisation of supports that effectively extend the right to read and learn.

The pictorial palimpsest of the 11th-century church, on the other hand, is narrated by a tactile catalogue. Its design involved a blend of art-historical knowledge for the textual content and various technologies for creating the Braille text and the raised line drawings of the frescoes. The drawings are the same as those present in the AR and VR applications (see Sections 4.1 and 4.2 for more details). Browsing through the catalogue, users can see or feel alternating texts along with their respective Braille transcriptions and colour images of the frescoes, whose outlines can be explored by touch. The colours of the frescoes were deliberately kept low-contrast for technical reasons (as otherwise the light would have swollen the dark colours of the frescoes and the black outlines) and to make the prominence of the raised lines more evident. Leaving the colours in this way also responds to the need to make the frescoes recognisable to both individuals with full sight and those with partial sight who wish to use the catalogue during their visit. From a technical point of view, the tactile catalogue consists of simple pages featuring printed text and a Braille transcription (created by the ITC of Lecce using an embossing technique that produces reliefs on paper with punches), as well as a special paper called Swell Touch Paper. This article, produced by various companies, including the well-known American Thermoform Corporation, contains microcapsules of black ink that swell when exposed to intense light, creating a raised line that can be felt by

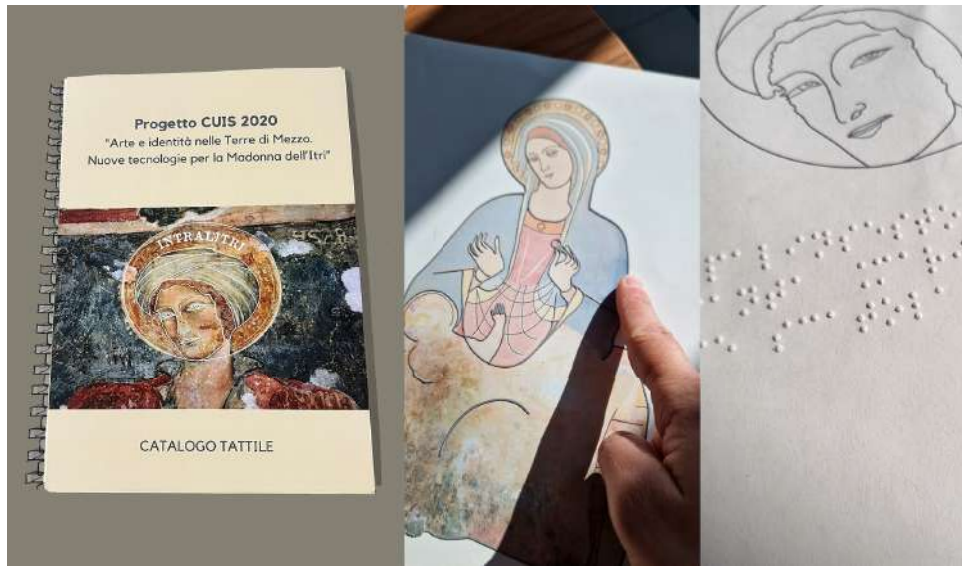


Fig. 7. Tactile catalogue. Central photo: drawing of the ‘Madonna of the Veil’ with touchable black raised lines. Right photo: Braille text created using the embossing technique.

touch. The choice of this tool was evaluated in collaboration with the ITC, which, due to its specific experience in aids for people with visual impairments, tested the ease of understanding the raised line drawings. One of the advantages of this technique is its cost-effectiveness, as it allows for the production of multiple copies at a low cost. Since the technique was implemented directly in the ITC with the Swell-Form Machine Zy-Fuse, several tests were conducted with different print samples submitted to specialised people. This enabled the selection of the contours of the frescoes that were most beneficial for comprehension and allowed for the precise calibration of their thickness, ensuring that the raised line drawings would be clear and legible once swollen. An entire A4 page of the catalogue has been dedicated to each fresco, so that they can be experienced in a simpler and more understandable way.

The catalogue cover was also paginated in both tactile and non-tactile formats, so as to allow anyone to access it. Finally, once all the prints were obtained, the pages were bound with a spiral binding, a choice motivated by the need to avoid compressing and affecting tactile elements such as Braille and raised line drawings (Figure 7).

This work has resulted in the creation of a complete tactile book that perfectly complements the sensory experience designed for the church of Madonna dell’Itri, culminating in a 3D print of the Byzantine structure (Figure 8).

The 3D print of the church, on a scale of 1:8 (width 40 cm, length 67 cm, height 32 cm), was made by Fablab Lecce, an association that hosts creative workshops with access to advanced machinery, educational activities and training courses (<https://fablablecce.org/>).

The same model visible within the VR application (see Section 4.2), complete with the gabled roof and apse dating from the Byzantine period, was exported in .STL format for 3D printing. The 3D printing followed the non-linear pattern of the church’s interior walls, and the sculptural elements, including the altar, were made separately, along with the movable roof that closes the structure. The printed model has been installed inside the new church preceding the entrance to the old building, near the panels, above a stand made by the company TR Inox.



Fig. 8. 3D-printed model of the church with the detachable roof and the sculptural apparatus inside.

Before printing, the 3D model of the church was divided into 28 parts to facilitate separate printing, after which the parts were joined with glue. The roof was designed to be detachable and to fit between the walls of the church. For its printing, the roof model was divided into six parts and then also joined with glue. The beams underneath the roof were made of plywood and then joined to the roof with glue. Once the roof is off, it is possible to investigate the walls of the church and the sculptural apparatus inside, which consists of the altar and the statues of Saint Peter and Saint Paul. Similarly, the altar was also separated into two parts before printing, while the two statues were printed in one piece each (Figure 8).

The entire 3D printing process was carried out with the UltiMaker 3 Extended printer, using PLA made from organic materials derived from corn waste. All the joints between the different moulded parts were then smoothed with sandpaper to make the separations less noticeable, both visually and to the touch. Finally, the entire model was painted with varnish.

This printed model allows for tactile exploration of the architectural structure. This particular field of investigation relates to the concept of the tactile museum, which is not opposed to the traditional idea of the museum but as its evolution, in which the involvement of sensory exploration amplifies the interaction with the accessibility of the artwork. The approach described here emphasises the importance of considering accessibility from multiple perspectives: physical, sensory, cognitive, digital and economic (e.g., by ensuring the presence of devices already in place or by addressing the needs of all visitors), transforming cultural sites into spaces where the community can meet and reimagine itself as welcoming and inclusive. Hence, the significance of tools such as those presented here to create new modes of enjoyment that cater to all ages, needs and art-historical interests.

5 Test and Results

To evaluate the user experience, an experimental campaign day was organised for which official communication was given through the local authorities. On this occasion, tests were conducted with 30 users (20 male and 10 female) with ages between 11 and 72 years according to the distributions shown in Figure 9.

Each user was asked to perform the same tasks without any particular time constraints. Immediately after the experience each user was asked to fill in a questionnaire consisting of items from the SUS, items from the

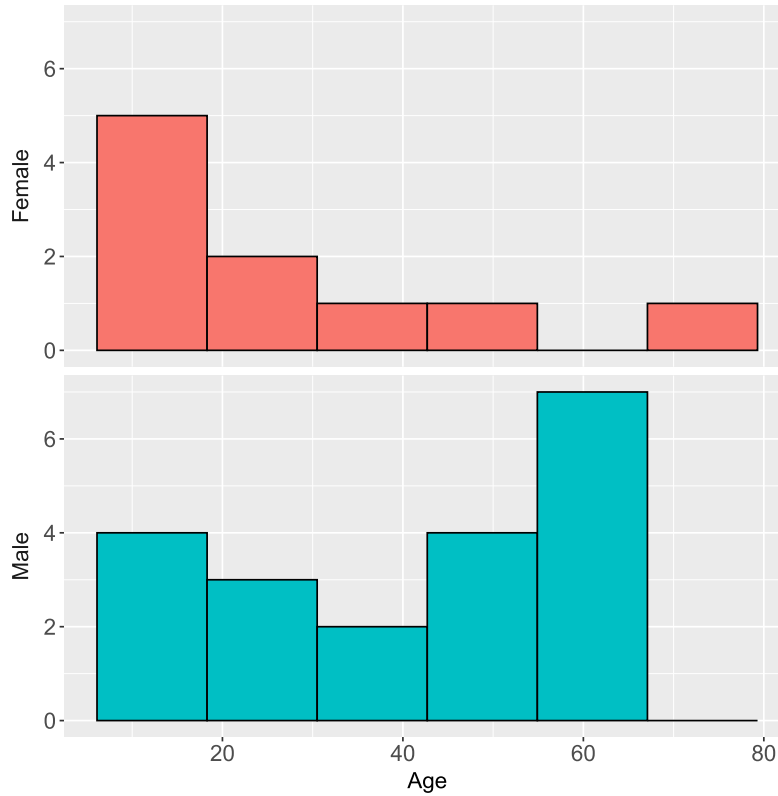


Fig. 9. Density plot of the ages of the users involved in the test.

Short UEQ, some additional custom items created from scratch and a final open-ended question asking for a brief assessment of the experience. By administering this questionnaire, VR and AR applications were evaluated not as isolated technological components, but as part of one overall experience on the basis of the following principles:

- *Ecological Validity and Holistic Approach to Experience*: Research in museology and user experience highlights that visitor perceptions emerge from the complex interaction of technology, content, context and personal expectations [5, 20]; evaluating the experience as a whole, rather than treating VR and AR as separate variables, enhances ecological validity (i.e., the ability to generalise findings to real-world settings) and provides a more meaningful holistic assessment;
- *Experience Coherence*: According to cognitive load theory and multimedia learning principles [35, 47], users integrate different inputs into a unified mental model to construct meaning; since the considered VR and AR applications contribute to a shared narrative and experiential goal, an overall evaluation of the whole system allows us to capture the perceived added value without disrupting the natural flow of the visitor's experience;
- *Use of Controls to Assess the Impact of Different Technologies*: This methodology does not disregard differences between VR and AR but rather contextualises them within a broader experience, thanks to specific questionnaire items (e.g., prior familiarity with VR and AR) assessing how previous exposure to these technologies might influence the overall perception; this approach aligns with research methodologies that analyse multimodal experiences using moderation measures rather than artificial separation [33].

Table 1. SUS Items

	SUS Items	Factors
1	You think you would like to use this system frequently	Usability
2	You found the system unnecessarily complex	Usability
3	You thought the system was easy to use	Usability
4	You think you would need the support of a technical person to be able to use this system	Learnability
5	You found that the various functions in this system were well integrated	Usability
6	You thought there was too much inconsistency in this system	Usability
7	You would imagine that most people would learn to use this system very quickly	Usability
8	You found the system very cumbersome to use	Usability
9	You felt very confident using the system	Usability
10	You needed to learn a lot of things before you could get going with this system	Learnability

Table 2. Short UEQ Items

	Short UEQ Items	Factors
1	Obstructive–supportive	Pragmatic Quality
2	Complicated–easy	Pragmatic Quality
3	Inefficient–efficient	Pragmatic Quality
4	Confusing–clear	Pragmatic Quality
5	Boring–exciting	Hedonic Quality
6	Not interesting–interesting	Hedonic Quality
7	Conventional–inventive	Hedonic Quality
8	Usual–leading edge	Hedonic Quality

The tactile models, on the other hand, were tested separately during development: thanks to a collaboration with the ITC of Lecce, it was possible to have in-progress validation by both people who are sighted and people who are blind specialised in sight-related accessibility issues, who confirmed the validity and effectiveness of the developed tactile models.

The SUS [9], made up of 10 items (Table 1) with five response options ranging from ‘Strongly Disagree’ to ‘Strongly Agree’, was included to evaluate two factors known to be weakly correlated [7, 29]: *Usability* in a strict sense and *Learnability*, which concerns the ability to quickly learn to use a system.

Items from the short version [44] of the User Experience Questionnaire [2] were then added, grouped into two factors (Table 2): *Pragmatic Quality*, which refers to the quality of interaction in the execution of tasks through the applications, and *Hedonic Quality*, which concerns the pleasant or enjoyable aspects of using the applications.

The custom items added to the application evaluation questionnaire are shown in Table 3. They were created to contextualise the use of the developed applications within the specific scenario of cultural interest.

The most reported responses to the final open-ended question described the experience as both interesting and exciting, as well as educationally valuable. Those who were already familiar with the church and its frescoes also stated that they had seen the various representative figures in a different guise.

Table 4 shows the mean values and SD of the factor scores of the SUS questionnaire expressed on a scale from 0 to 100%. *Usability* has a fairly high average score, while *Learnability* has a lower average score but also greater variability evidenced by the higher SD.

Table 3. Additional Questionnaire Items

	Custom Items	Labels	Response Type
1	You had already used a VR headset before this experience	-	Yes/No
2	You had already used an AR application before this experience	-	Yes/No
3	You have learnt something new thanks to this system	LearnedSomethingNew	Likert scale 1 to 7
4	The duration of the user experience is right	RightDuration	Likert scale 1 to 7
5	The contents of the applications are interesting	InterestingContent	Likert scale 1 to 7
6	The audio content helps in exploring the scenario	HelpfulAudioContent	Likert scale 1 to 7
7	You would recommend this experience	ExperienceToRecommend	Likert scale 1 to 7

Table 4. Mean Values and SD of the *Usability* and *Learnability* Scores from the SUS Questionnaire Expressed on a Scale from 0 to 100%

Factor	Mean	SD
Usability	83.542%	13.231%
Learnability	67.083%	27.166%

The distribution chart of *Usability* in Figure 10 shows that most of the scores are concentrated around the 80% and 90% values. The *Learnability* chart, on the other hand, still has a peak around 80%, but also a more evident tail on the left, representing the difficulties some users had in learning to use the applications.

Table 5 shows the mean values and SD of the factor scores of the Short UEQ questionnaire expressed on a scale of -3 to 3 .

The distribution charts of *Pragmatic Quality* and *Hedonic Quality* depicted in Figure 11 have a rather wide tail on the left, denoting greater variability in users' opinions. For both factors, however, no particular clusters of scores are noticeable.

Table 6 shows the mean values and SD of the scores of the additional questionnaire items expressed on a scale from 0 to 6. Nearly all users say they would recommend the experience to others, as revealed by the high mean value and the low SD, which suggests a high level of agreement among users' opinions. For the other factors, there is less convergence of users' opinions towards a single score, as shown by the larger SD: the diagram of the distributions in Figure 12 shows for each of them a prevalence of values around the highest score, but also a smaller cluster around more moderate scores. In particular, the cluster around moderate scores is more evident for the factor representing the perception of having learnt something new, which is the one with the highest SD.

5.1 Differences between User Groups

The scores of the factors were also compared between different groups of participants divided by gender, age, any previous VR experience and any previous AR experience by means of Kruskal-Wallis rank sum tests.

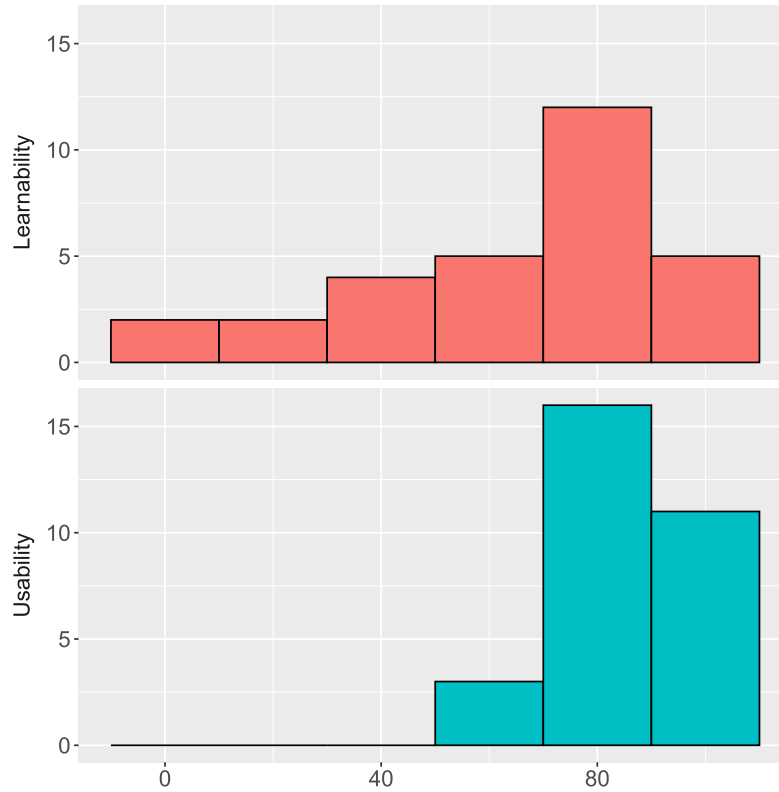


Fig. 10. Distributions of *Usability* and *Learnability* scores expressed on a scale from 0 to 100%.

Table 5. Mean Values and SD of the *Pragmatic* and *Hedonic Quality* Scores from the Short UEQ Questionnaire Expressed on a Scale from -3 to 3 .

Factor	Mean	SD
Pragmatic Quality	2.583	0.592
Hedonic Quality	2.575	0.479

The test applied to gender division revealed no significant differences between male and female users, as the p-value, shown in Table 7, is greater than 0.05 for all factors considered.

In the comparison between users with previous experience with VR and those without previous experience, the Kruskal-Wallis test revealed a significant difference in terms of *Pragmatic Quality*, as shown in Table 8.

The diagram in Figure 13 compares the distributions of *Pragmatic Quality* between users with previous VR experience and users without previous VR experience. The histograms show high *Pragmatic Quality* values for more than 80% of users without previous VR experience and slightly more than 40% of users with previous VR experience: for the second group of users there is still a prevalence of high values, but the scores have a more balanced distribution.

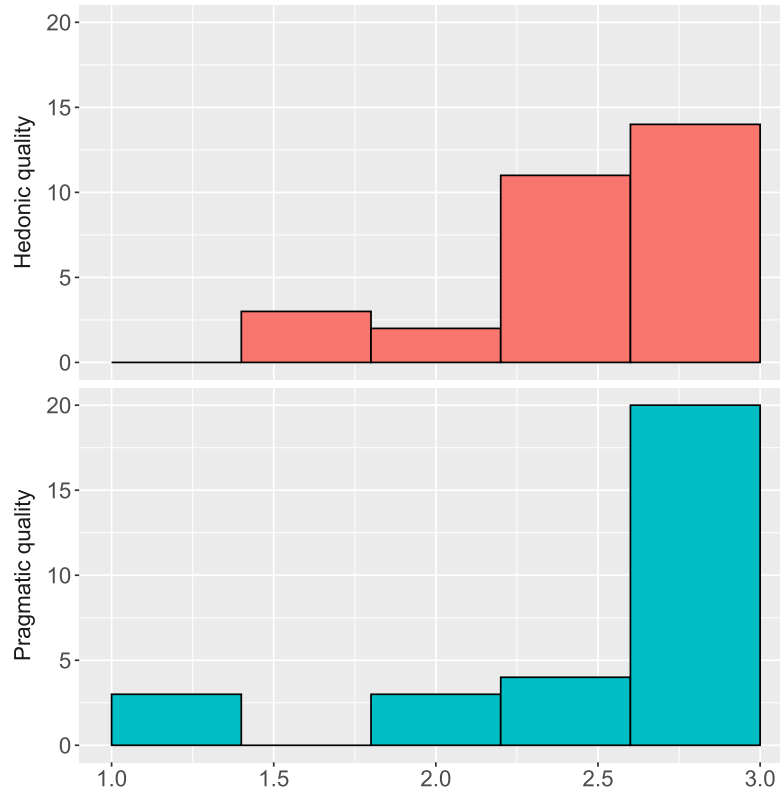


Fig. 11. Distributions of *Pragmatic* and *Hedonic* quality scores expressed on a scale from -3 to 3 .

Table 6. Mean Values and SD of the Scores of the Additional Questionnaire Items Expressed on a Scale from 0 to 6

Factor	Mean	SD
LearnedSomethingNew	5.133	1.074
RightDuration	5.433	0.858
InterestingContent	5.633	0.669
HelpfulAudioContent	5.733	0.583
ExperienceToRecommend	5.933	0.254

In the comparison between users with previous experience with AR and those without previous experience, the Kruskal-Wallis test revealed significant differences in terms of both *Pragmatic Quality* and *Hedonic Quality*, as shown in Table 9.

The diagram in Figure 14 compares the distributions of *Pragmatic* and *Hedonic Quality* between users with previous AR experience and users without previous AR experience. Again, *Pragmatic Quality* scores very high for more than 80% of users without previous AR experience and slightly more than 40% of users with previous AR experience. *Hedonic Quality*, on the other hand, has very high values for 60% of users with no previous

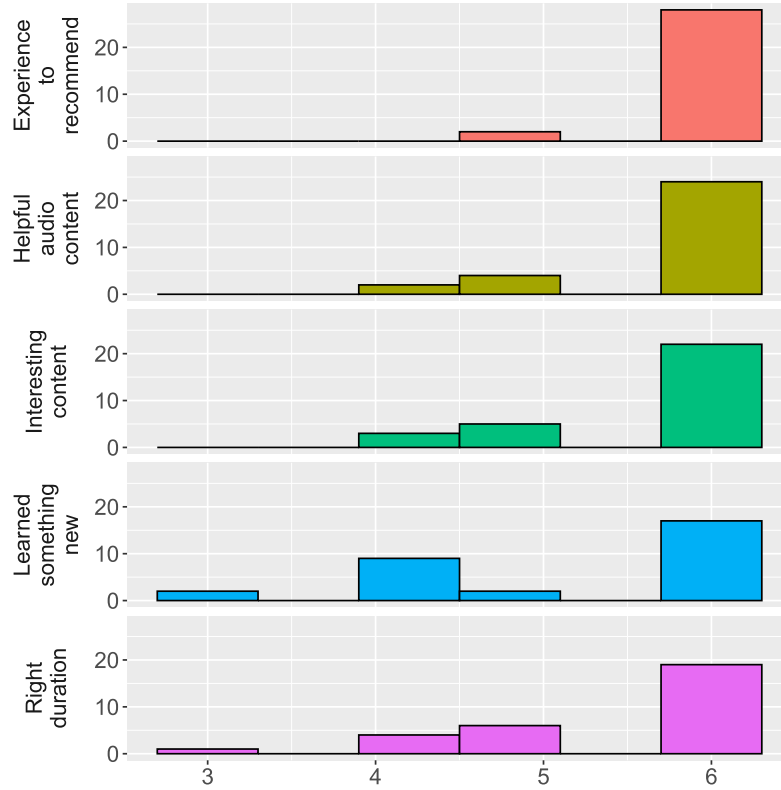


Fig. 12. Distributions of additional factor scores expressed on a scale from 0 to 6.

Table 7. Kruskal-Wallis Rank Sum Test Comparing Factor Scores between Male and Female Users

Factor	χ^2	P-Value
LearnedSomethingNew	3.170	0.075
RightDuration	0.000	1.000
InterestingContent	3.197	0.074
HelpfulAudioContent	0.673	0.412
ExperienceToRecommend	1.036	0.309
PragmaticQuality	0.223	0.637
HedonicQuality	0.009	0.925
Usability	0.159	0.690
Learnability	1.152	0.283

AR experience and around 25% for users with previous AR experience, for whom medium-high values are predominant at 40%.

To assess a possible impact of age on the user experience factors, users were divided into four age groups through the *k*-means method, as suggested by the *NbClust* package for R [13]. The mean values and SD of the scores calculated for the four identified age ranges are shown in Tables 10 and 11, respectively.

Table 8. Kruskal-Wallis Rank Sum Test Comparing Factor Scores between Users with Previous VR Experience and Users without Previous VR Experience

Factor	χ^2	P-Value
LearnedSomethingNew	1.651	0.199
RightDuration	0.879	0.349
InterestingContent	0.060	0.806
HelpfulAudioContent	0.531	0.466
ExperienceToRecommend	3.107	0.078
PragmaticQuality	5.156	0.023
HedonicQuality	2.077	0.150
Usability	1.048	0.306
Learnability	1.452	0.228

Bolded p-values (< 0.05) indicate statistically significant differences between the two user groups.

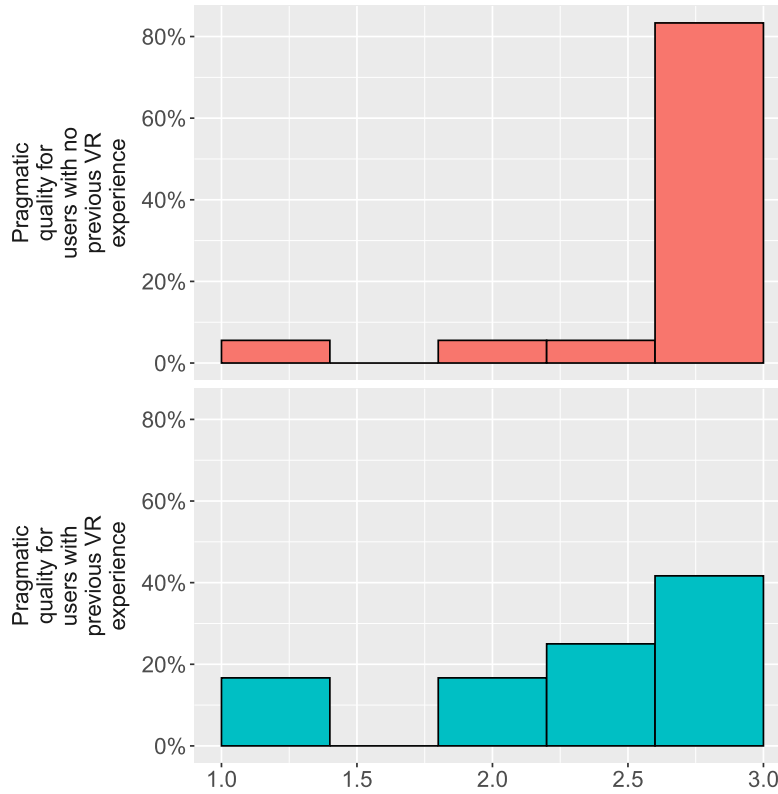


Fig. 13. Comparison of *Pragmatic Quality* distributions of users with previous VR experience and without previous VR experience.

A comparison carried out by means of a Kruskal-Wallis test, shown in Table 12, suggested a potential impact of age on *Pragmatic Quality* and on the intention to recommend the experience to others. However, only the

Table 9. Kruskal-Wallis Rank Sum Test Comparing Factor Scores between Users with Previous AR Experience and Users without Previous AR Experience

Factor	χ^2	P-Value
LearnedSomethingNew	5.110	0.024
RightDuration	0.103	0.748
InterestingContent	0.967	0.326
HelpfulAudioContent	0.531	0.466
ExperienceToRecommend	3.107	0.078
PragmaticQuality	7.424	0.006
HedonicQuality	5.805	0.016
Usability	0.383	0.536
Learnability	2.205	0.138

Bolded p-values (< 0.05) indicate statistically significant differences between the two user groups.

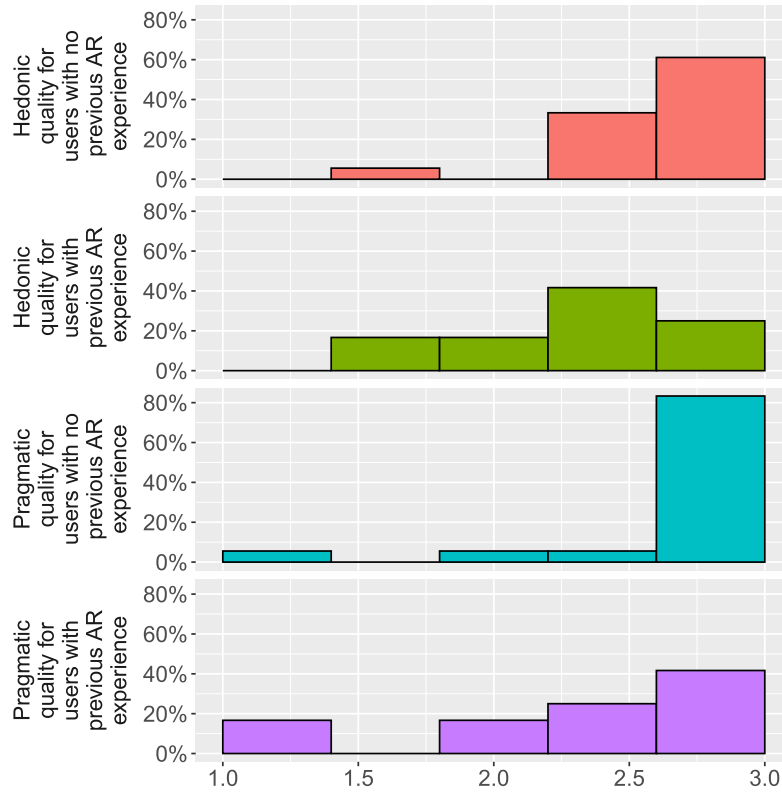


Fig. 14. Comparison of *Pragmatic* and *Hedonic Quality* distributions of users with previous AR experience and without previous AR experience.

second age group, consisting of users aged between 24 and 36, did not express the highest average score for *ExperienceToRecommend*, but still scored only slightly below the maximum value.

Table 10. Mean Values of User Experience Factor Scores Calculated for Users of Different Age Groups

Age Interval	11–22	24–36	44–56	58–72
LearnedSomethingNew	4.727	5.000	5.333	5.714
RightDuration	5.636	4.667	5.667	5.571
InterestingContent	5.636	5.000	6.000	5.857
HelpfulAudioContent	5.818	5.500	5.667	5.857
ExperienceToRecommend	6.000	5.667	6.000	6.000
PragmaticQuality	2.659	2.000	2.583	2.964
HedonicQuality	2.477	2.417	2.583	2.857
Usability	83.239%	81.771%	85.417%	83.929%
Learnability	64.773%	70.833%	77.083%	58.929%

Table 11. Standard Deviations of User Experience Factor Scores Calculated for Users of Different Age Groups

Age Interval	11–22	24–36	44–56	58–72
LearnedSomethingNew	1.104	1.095	1.211	0.756
RightDuration	0.505	1.211	0.816	0.787
InterestingContent	0.674	0.894	0.000	0.378
HelpfulAudioContent	0.405	0.837	0.816	0.378
ExperienceToRecommend	0.000	0.516	0.000	0.000
PragmaticQuality	0.358	0.791	0.719	0.094
HedonicQuality	0.493	0.585	0.516	0.244
Usability	14.271%	8.709%	19.331%	11.184%
Learnability	30.526%	12.910%	18.400%	37.301%

Table 12. Kruskal-Wallis Rank Sum Test Comparing Factor Scores between Users of Different Age Groups

Factor	χ^2	P-Value
LearnedSomethingNew	4.148	0.246
RightDuration	4.534	0.209
InterestingContent	7.878	0.049
HelpfulAudioContent	0.999	0.802
ExperienceToRecommend	8.286	0.040
PragmaticQuality	8.835	0.032
HedonicQuality	3.677	0.298
Usability	0.640	0.887
Learnability	0.971	0.808

Bolded p-values (< 0.05) indicate statistically significant differences between the two user groups.

Surprisingly, there seems to be no influence of age on *Usability*, which remains above 80% for all four user groups. *Learnability* has the lowest average value for the oldest age group but also shows high variability for this age group and the youngest group, as suggested by the high SD.

Table 13. Dunn's Test Comparing *Pragmatic Quality* Scores between Users of Different Age Groups

Comparison	Z	P-Value	Adjusted P-Value (Bonferroni)	Ad- justed P-Value (Holm)	Ad- justed P-Value (Sidak)	Ad- justed P-Value (HS)	Adjusted P-Value (Hochberg)	Ad- justed P-Value (BH)	Ad- justed P-Value (BY)
11–22 to 24–36	1.555	0.120	0.719	0.360	0.535	0.318	0.360	0.180	0.441
11–22 to 44–56	−0.566	0.572	1.000	0.572	0.994	0.572	0.572	0.572	1.000
24–36 to 44–56	−1.864	0.062	0.374	0.311	0.320	0.275	0.311	0.187	0.458
11–22 to 58–72	−1.725	0.085	0.507	0.338	0.411	0.298	0.338	0.169	0.414
24–36 to 58–72	−2.918	0.004	0.021	0.021	0.021	0.021	0.021	0.021	0.052
44–56 to 58–72	−0.983	0.326	1.000	0.651	0.906	0.545	0.651	0.391	0.957

Bolded p-values (< 0.05) indicate statistically significant differences between the two user groups.

A Dunn's test was carried out to determine exactly which groups are different in terms of *Pragmatic Quality*. As reported in Table 13, the test showed a significant difference between users aged between 24 and 36 and those aged between 58 and 72 (since almost all corrected p-values for this comparison are less than 0.05). In fact, the difference in mean values shown in Table 10 is highest just between the groups of users belonging to these two age groups.

5.2 Correlations between User Experience Factors

In order to assess possible correlations, a hierarchical cluster analysis was conducted on all the questionnaire scores with the ICLUST package for *R* [42]. Clusters are represented by oval shapes in the diagram of Figure 15: each of them contains the Cronbach's alpha [17], which is a measure of internal consistency and the Revelle's beta [43], which represents the scale homogeneity. The diagram shows that *Usability* and *Learnability* do not influence either *Pragmatic* and *Hedonic Quality* of the system or users' opinions on the experience in general, expressed by the other items added to the questionnaire. Interest in content is also not affected by *Pragmatic* or *Hedonic Quality*.

It is interesting to note the close correlation between *Hedonic Quality* and the help provided by the system's audio component in the scenario exploration. The combination of these factors also appears to be correlated with the belief that the duration of the experience was appropriate and somewhat influences the perception of having learned something new. The macro-cluster composed of all these factors is then correlated with the perception of *Pragmatic Quality*.

6 Discussion

Several insights emerge from the data analysis conducted in the previous section. First of all, the system proved to be very user-friendly for users of all ages. The value of the *Learnability* factor, which is lower than that of *Usability*, suggests that the greatest difficulties were mainly in the initial stages, in which they had to become familiar with the technologies. However, these difficulties did not significantly affect the level of appreciation of the technologies adopted, which remains high as suggested by the *Pragmatic* and *Hedonic Quality* values, and of the experience in general, since many users would like to recommend it to others. The highly variable *Learnability* denotes a great variability in the learning curve especially among older users, but this did not influence their extremely positive judgements on the usefulness of the system, represented by the *Pragmatic Quality* concept, which were even better than those expressed by younger users.

However, the data analysis highlighted a partial decrease in *Pragmatic Quality* for users with previous VR and AR experience, probably due to increased expectations and a greater awareness of the limitations of VR in general. For users with previous AR experiences, in particular, the data analysis also revealed a partial decrease

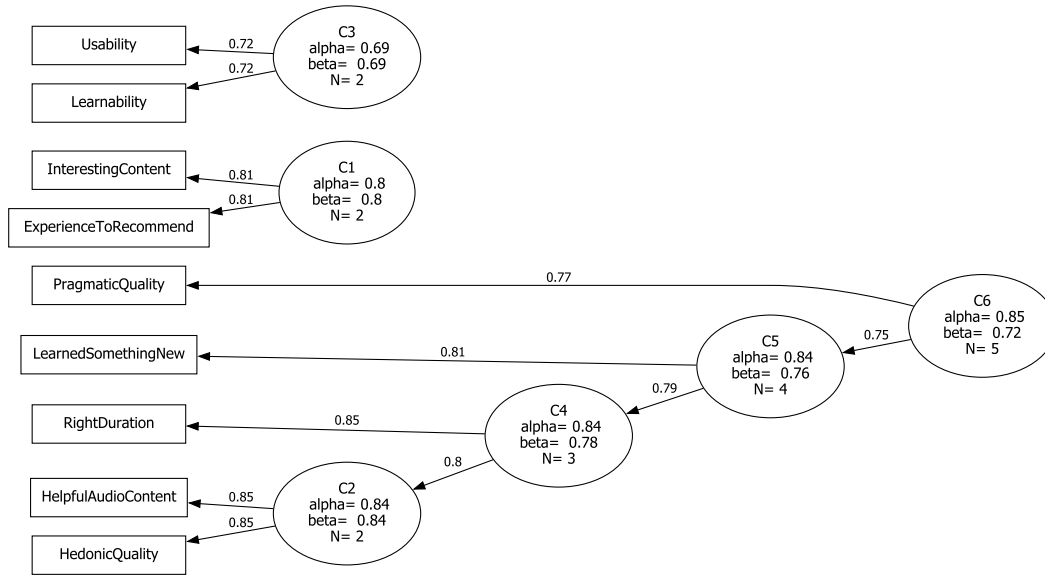


Fig. 15. Cluster analysis of the user experience factors (Cluster fit = 0.84, Pattern fit = 0.98, RMSR = 0.08).

in *Hedonic Quality*, which did not emerge from the responses of users with previous VR experiences: this is probably related to the fact that VR can rely on a greater versatility and ability to completely isolate the user, favouring new and immersive experiences that maintain high hedonic involvement, even for more experienced users. Despite these differences between user groups, no decrease in interest in the content of the experience was observed. Moreover, many users highlighted the educational potential they saw in the whole experience. The system was designed, at least for the time being, for an informal learning scenario [32], in which learning is not tied to institutional contexts and is mainly fuelled by simple curiosity: in such a context, VR and AR technologies can leverage curiosity and push users to learn through autonomous exploration.

An interesting aspect that emerged from the cluster analysis is the close correlation between the help provided by the audio in the exploration of the scenario and the *Hedonic Quality*. Audio support enhances *Hedonic Quality* by increasing user enjoyment, immersion and emotional engagement. It contributes in making the experience more realistic and aesthetically pleasing, by creating a stronger sense of presence. It helps guide users intuitively, reducing cognitive load and enabling smoother interactions. Additionally, it can evoke positive emotions and intensify responses, making the experience not only functional but also deeply satisfying and memorable.

To answer the research questions raised in section X, several insights can be highlighted from the analysis of the data, which show that XR technologies can indeed play a significant role in improving accessibility and engagement at heritage sites.

Regarding Q1, the system's generally high usability and learnability suggest that XR technologies, such as VR and AR, can effectively support accessibility across diverse visitor groups, by providing an accessible and intuitive interface. The strong Pragmatic Quality ratings indicate that users found the system helpful for navigating and understanding the cultural site. Additionally, the audio guidance proved instrumental in enhancing cognitive accessibility by reducing cognitive load, particularly in complex settings, which is essential for making cultural content more approachable and inclusive.

For Q2, the combination of XR technologies, digital restoration elements and audio-tactile aids appears to provide a richer, more inclusive experience, aligning with the goal of offering both informative and immersive exploration of the site's historical context. This not only enhances the informational value of the experience but

also ensures that it is memorable and emotionally resonant, regardless of prior knowledge or physical ability. In addition, in answering the open question, one user stated that he experienced a change in his perception of the works of art and spaces of the church that he was already familiar with: the use of XR technologies, in particular for superimposing virtual elements on real ones, not only made the site more accessible, but also allowed the user to rediscover significant details in a ‘different guise’, a new way of seeing and interpreting the frescoes and figures depicted in the church. This testimony confirms that the approach adopted has the power to offer visitors a deeper and more multifaceted interpretative experience, allowing them to perceive details and meanings that might otherwise go unnoticed. As a result, the system not only informs, but invites users into a new form of cultural exploration, stimulating critical observation and reflection on what they see.

In response to Q3, the data suggest that digital strategies can indeed enhance accessibility and strengthen connections between the local community and cultural heritage. The system’s appeal across age groups and skill levels points to its potential as a tool not just for individual learning but for community engagement. Furthermore, the high level of user satisfaction and the willingness to recommend the experience highlight the role of XR in reinforcing cultural ties, as it provides a bridge between past and present through engaging digital narratives.

7 Conclusions and Future Work

In conclusion, the implementation of the ‘Intra l’Itri’ project has significantly advanced the accessibility and preservation efforts for the church of Madonna dell’Itri in Nociglia, Italy, leveraging state-of-the-art XR technologies. The church’s rich historical narrative, encapsulated within its ancient pictorial palimpsest and structural transformations, presented a unique challenge, met through collaborative endeavours supported by the Salento Interprovincial University Consortium (Consorzio Universitario Interprovinciale Salentino - CUIS 2020). This interdisciplinary approach, involving the University of Salento’s Department of Engineering for Innovation, Department of Cultural Heritage, the Municipality of Nociglia, local stakeholders and professionals, yielded promising results. By focusing on the latest advancements in AR and VR applications, alongside innovative 3D and tactile prints, the project aims to validate a digital strategy that enrich visitor experiences and conserve this invaluable cultural asset. The findings from the initial testing phase underscore the efficacy of the adopted approach in enhancing accessibility and engagement with the church’s historical and artistic significance, setting a precedent for future conservation and immersive cultural heritage projects. Besides traditional usability, the questionnaire administered after the tests assessed the perception of content, *Pragmatic Quality*, which is the quality of interaction in the execution of tasks through the applications, and *Hedonic Quality*, which concerns the pleasant or enjoyable aspects of using the applications. Older users and those who had no previous experience with VR and AR had no particular usability problems when using the applications, but just needed a little more time at the beginning to familiarise themselves with them, as evidenced by the lower scores for the *Learnability* factor. However, it is important to emphasise that these difficulties did not affect the extremely positive assessment of the experience as a whole and the interest shown in the content on which it focused: some users emphasised the fascinating and exciting side of the experience, while others praised its potential from an educational point of view. In addition to the technical advancements and practical outcomes of the ‘Intra l’Itri’ project, it is essential to underscore the broader significance of intervening to enhance accessibility in peripheral and decentralised cultural sites, distant from mainstream tourist circuits. These sites often possess rich historical and artistic value yet face challenges in terms of visibility, preservation and visitor engagement. By focusing on the church of Madonna dell’Itri in Nociglia, Italy, the project not only aimed to improve accessibility but also sought to amplify the voices of culturally marginalised regions. This intervention serves as a testament to the intrinsic worth of these peripheral sites, shedding light on their unique narratives and contributions to collective heritage. Moreover, by fostering accessibility and inclusivity in such locations, the project explores the way for more equitable distribution of cultural resources and tourism opportunities, fostering sustainable development and community empowerment. Thus, this project underscores the importance of prioritising interventions in

peripheral cultural sites as integral components of broader cultural heritage conservation and inclusive tourism strategies. For future work, it is crucial to emphasise the significance of involving local cultural operators, such as tour guides, in the ongoing development and implementation of the project. These individuals play a pivotal role in facilitating visitor experiences and interpreting the cultural significance of the church of Madonna dell'Itri and its surroundings. By providing training sessions on how to utilise the devices and applications developed through the project, the staff empower these operators to seamlessly integrate digital tools into their guided tours and educational programs. This ongoing training initiative will ensure the sustainability and effectiveness of this interventions, fostering a symbiotic relationship between technological innovation and local expertise. Furthermore, by equipping local cultural operators with the necessary skills and knowledge, the project not only enhances the accessibility and quality of visitor experiences but also contributes to capacity-building and economic empowerment within the community. Moving forward, continued collaboration and engagement with local stakeholders will be essential to maximise the long-term impact of this project and promote the sustainable development of cultural tourism in the region.

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Contribution

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