

Review

Digital Heritage, the Possibilities of Information Visualisation through Extended Reality Tools

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Abstract: Many researchers in the field of cultural heritage point to the justification of the use of extended reality to present digital heritage. Research studies, but mainly user reactions, have responded to experiences with extended reality with a positive response. Technological research in the field of extended reality is advancing rapidly. In this review, we will cover the current possibilities and trends of extended reality. Specifically, we will focus on the application in creating interactive multimedia exhibitions in museums and galleries and presenting 3D digital heritage. We believe the practical examples shown will be an inspiration for application developers, content creators, and exhibition curators. Awareness of the possibilities and limits of the current state of technological progress is an essential requirement for utilisation of the full potential of extended reality.

Keywords: digital heritage; augmented reality; cultural informatics; extended reality; information and communication technologies; virtual museum



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1. Introduction

According to Silverstone, museums are in many aspects the same as today's other media. They try to inform and entertain, educate, and please. In their exhibitions, they tell stories and open up opportunities for discussion. They define. Whether consciously or unconsciously, effectively or inefficiently, the programme of their exhibition stimulates the mind to think. Things that are otherwise unknown and misunderstood are presented to curious visitors in clear language [1].

Shifting through the digital era, we encounter new challenges. In museology, such a challenge is brought by digital heritage (DH). Many scientists and professionals are focused on the process of DH creation [2], data storage and sharing [3], and information visualisation and object interaction [4], where extended reality (XR) tools play a significant role.

DH is an abstract term. UNESCO defines digital heritage as any digital material referring to our heritage that has value and needs to be preserved [5]. It includes cultural, educational, scientific, or administrative information, as well as technical, medical, or other information created ("born") digitally or converted to digital form from existing analogue sources.

The scientific community deals with the term digital heritage in a broader sense. It connects it with information and communications technologies (ICT), their practical application and technological approaches to the demands of cultural and natural heritage, searching for a way to connect digital media and our cultural heritage [6]. Research in this field, therefore, includes and combines knowledge and new findings from several scientific disciplines [7], from the history of art to technical sciences, from archiving to analysis and statistics, from archaeology to design art, from museology to computer graphics, etc.

The main focus of this article is to describe the possibilities of XR tools in interactive museum exhibitions. To cover the whole problematic, we briefly describe the process of

DH creation on an example of digitisation of objects in the Wallachian Open Air Museum, Rožnov pod Radhoštěm. The fourth chapter defines the term XR and its subvariants. The possibilities of XR in DH presentation are demonstrated using practical examples. The last chapter points to the current situation, highlighting the significant research activities of fellow scholars and professionals in the field of DH and XR technological development. It is intended to serve as a starting point for other researchers who would like to begin new research, follow up with or connect to the work of researchers in the field of XR.

2. Review Objective

This article aims to outline the possibilities XR tools provide in the process of multimedia exhibition creation in museums and galleries. The potential of XR technology is demonstrated using selected examples from practice, which show an excellent incorporation of key features for the successful combination of XR and DH.

Some groups of scientists are engaged in the process of digitising cultural heritage and creating content (3D models) for XR applications and virtual museums [8]. Other researchers devote their energy to finding the proper approach to interpreting digital heritage to ensure those interested in this type of content find their way to discover the information [9]. However, the last piece of the puzzle is missing—to determine the characteristics, key features, and functionality that the “ready to go” XR application will have and define what tools it will use for interaction with the content presented.

Traditionally, the attempt to present digital heritage via XR at exhibitions ends with a static display of the 3D model on the device display without the possibility of further interaction with the user. However, current technologies allow for significantly more.

3. Digital Heritage, the Process of Digitisation

How is DH being born? While some DH is born under the virtual pen of digital artists [10], some other DH is born via digitisation of actual historical artefacts and archaeological sites. The digitisation is executed using photogrammetry and laser scanning technology. Most of the knowledge and information in this article comes from practical and theoretical experience our team learned through the implementation of the project to digitise cultural heritage (CH) in the open-air museum, Wallachian Open Air Museum, Rožnov pod Radhoštěm, Czech Republic ¹. This museum is unique with its collection of industrial buildings of regional importance from the turns of the 19th and 20th centuries. The complex has functional technical water management monuments (fulling machine, mill, sawmill, hammer mill, and oil mill), which point to the coexistence of humans with nature and their ingenuity and intelligence to use natural forces (in this case water energy) to their advantage. Industrial monuments are the bearer of architectural, historical, and technical values of the nation; they represent material evidence of the production and development of industry [11]. In addition to industrial monuments, the extensive complex includes sets of other wooden buildings. The exhibition demonstrates the everyday life of people in Wallachia from the end of the 18th century to the 1950s.

Selected objects of the museum were surveyed and documented using the terrestrial laser scanning method in combination with ground and aerial photogrammetry technology. The procedure of surveying and preparing the digital 3D models is described in more detail in the article “Digital Archiving of Historical Water Utilization Structures Using an Interdisciplinary Method”, published in the journal *GeoScience Engineering* [12]. The process of DH digitisation, from surveying the object of interest and data processing to DH visualization and presentation in XR, assembled by our team during the digitization of the Wallachian Open Air Museum, is schematically described in Figure 1.

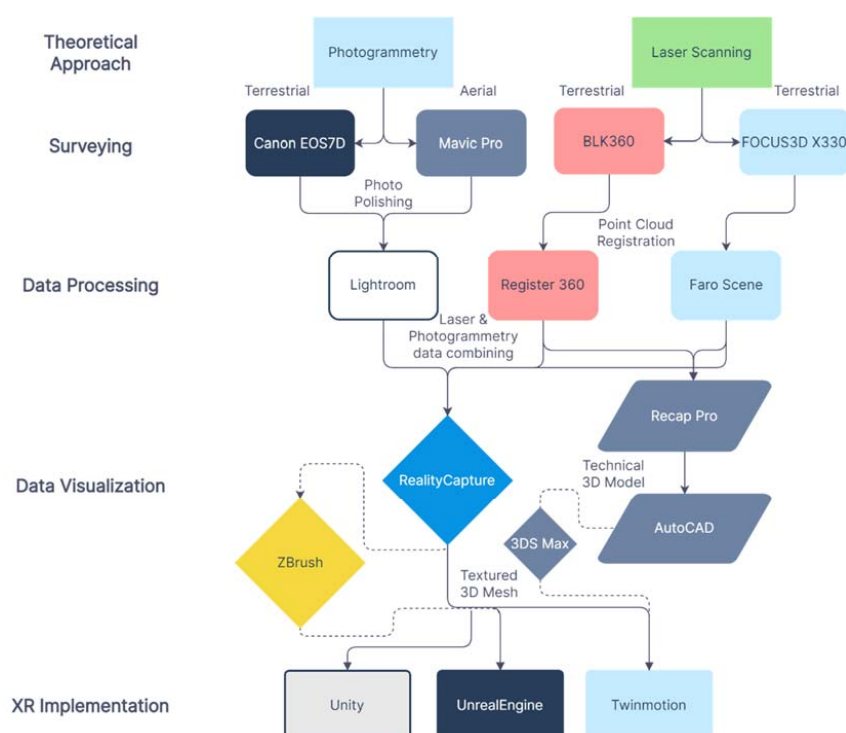


Figure 1. Workflow of DH digitisation, from surveying of CH to DH presentation in XR.

To create DH is just a first step in the management process. It is important to solve how to store the digital data, present and visualise, and spread the stored information. Three-dimensional models of documented objects serve diverse applications. For the purpose of the virtual tour of the museum, the 3D models were incorporated into the virtual worlds created using Twinmotion and Unity software (Figure 2).



Figure 2. Visualisation of a waterman statue, Rožnov, open-air museum. Twinmotion.

Furthermore, with the help of Unity, mobile XR applications were created to enrich the existing exhibition directly in the museum.

To provide a broader view of the possibilities of applying XR in the field of museology and presentation of digital heritage, we will not limit the article to only digital products

created by us, but also present other similar projects. This article uses practical examples to demonstrate the specific possibilities of developing AR and VR applications intended for multimedia exhibitions.

4. eXtended Reality, the Introduction to New Realities

Museums are interested in the digitisation of their collections not only for the purpose of preserving cultural heritage but also in order to convey the information stored in their collections to the general public in an attractive way. The evolving XR technologies have not often been chosen as a tool to create digital exhibitions in a virtual museum and enrich the visitor experience during a museum or gallery tour, but this is changing now, and they are being employed more and more frequently.

Extended reality is a term referring to all real and virtual combined environments and human–machine interactions generated using computer technology and wearable devices. It includes three specific forms: augmented reality (AR), virtual reality (VR), mixed reality (MR), and the areas interpolated between them [13]. It can be difficult to understand the differences between AR, MR, and VR. Therefore, it is necessary to define these and related terms in more detail (Figure 3). It is particularly hard to demonstrate the differences between AR, MR, and VR in the limited space of one paragraph. We include examples of specific XR applications and encourage the readers concerned to try to use them and experience the differences and XR possibilities on their own.

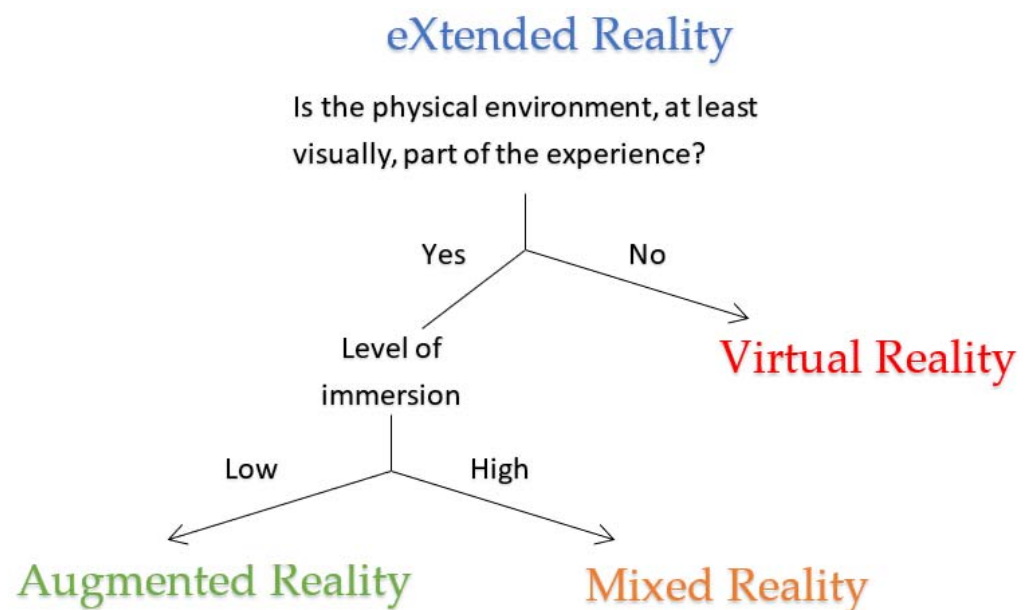


Figure 3. Extended reality. Specific forms of XR.

Of the above, VR is the most well-known technological concept with which the general public comes into contact more and more often. With the aid of a display device—a head-mounted display (HMD), the so-called VR headset, the user is transported to the virtual world, an alternative reality. The user can move, manipulate, and interact with objects in the virtual environment. Computer-generated visual effects mediate the VR experience, usually enriched with an audio component with 3D sound support. In this concept, the VR application evokes the most realistic experience from the perception of a virtual environment [14]. The easily accessible VR “experience” is provided to the general public using the YouTube VR service (alternative name: YouTube 360). The service includes a vast library of special videos captured with a 360° panoramic camera and videos created digitally specifically to be watched in VR. Using an XR device—a VR headset—or just using a tablet or smartphone, the viewer can rotate the view of the camera. Thanks to the movement of the camera from the point of view of the first person, the observed scene in the

video acquires a dynamic dimension; it literally draws the viewer into the story. Watching 360° videos using a HMD increases the sense of personification of the viewer in the story and amplifies their emotions (joy, enthusiasm, feeling of fear), as confirmed by scientific studies [15]. YouTube VR provides easily accessible VR content. However, these are very limited here in the perspective of the possibilities offered by VR. Not only according to the VR gaming community, but also considering the number of awards collected, *Half-Life Alyx*, a game set in a sci-fi environment, provides one of the best VR experiences. Using the Source 2 engine, game developers managed to create a game system that allows the player to make decisions and perform actions as in the real world when navigating virtual environments, thanks to excellent interaction of the player with the environment (Figure 4b,c).

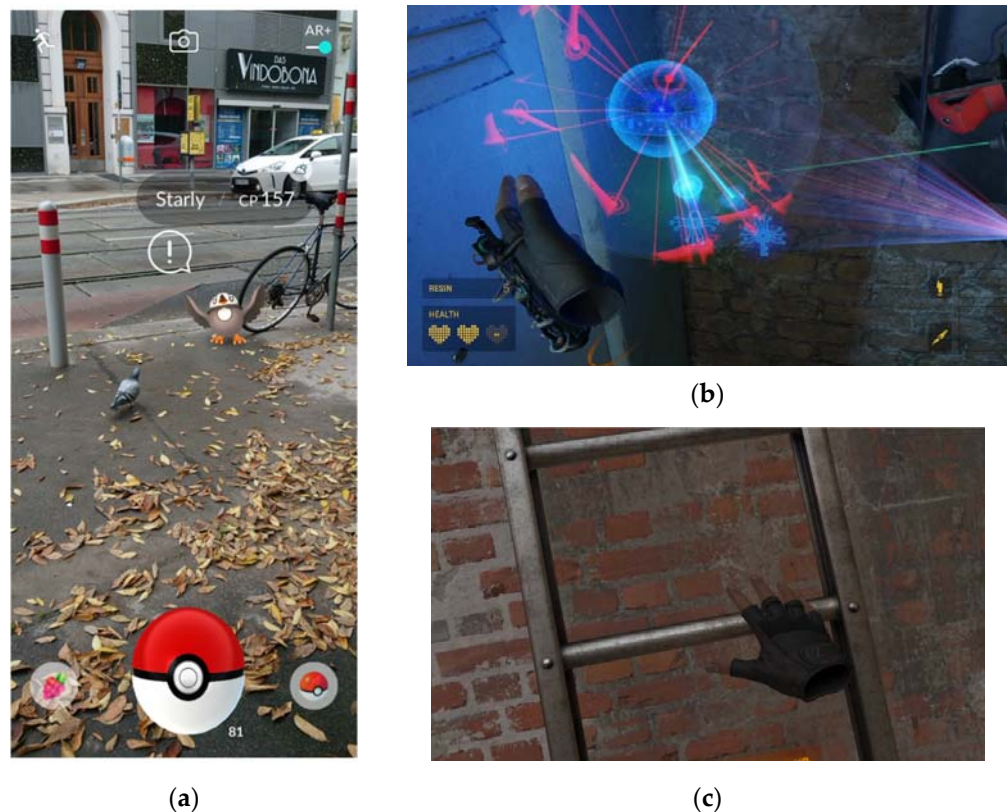


Figure 4. XR application examples. (a) Catching a monster in AR, Pokémon GO; (b) solving a VR puzzle, Half-Life Alyx; (c) climbing a ladder via hand movements in VR, Half-Life Alyx.

On the contrary, augmented reality works with a real environment enriched using digital information [16]. The principles of AR can be introduced using the example of the world's most widespread AR mobile application, Pokémon GO [17]. The application is able to visualise virtual creatures seamlessly positioned in a real environment (Figure 4a). A closer perspective of AR will be described in more detail using examples of functional applications developed to present digital heritage; these applications are described in a later chapter.

Mixed reality requires demanding technological solutions to capture the movement of the user and the surrounded environment and objects—real and virtual, with which they can interact and manipulate. So far, experimental MR deployment has been used by research laboratories, experimental centres, and universities [18]. The Microsoft HoloLens project has achieved the most tangible accomplishments in the field of MR. Other devices from technology companies such as Samsung, Acer, HP, Dell, and Lenovo are also present in the MR market. However, it should be noted that there are multiple perspectives on the definition of XR. The opinions of both scientists and XR industry professionals differ

the most when it comes to the definition of MR [19]. With the launch of devices such as Microsoft HoloLens, Magic Leap, or Google Glass, the term MR is shifting towards the designation “realistic AR”.

What kind of benefits do the combination of DH and XR deliver? The incorporation of information technologies into a gallery or museum exhibition is characterised by an effort to shift the visitor experience from a static to a dynamic level. XR provides solutions to some of the problems associated with creating an exhibition. XR offers possibilities for how to solve problems with limited space, and it provides elegant solutions on how to include information in several foreign languages in the exhibition. The exhibition of digital copies represents a more affordable option for borrowing rare artefacts, which may not even be available for borrowing on the required date due to the busy schedule of museums. XR reduces the final cost of creating an exhibition [20], alleviates the curator’s concerns about the fragility of the exhibited objects, and, at the same time, provides the curator of the exhibition with almost unlimited creative possibilities [21].

5. Examples of the Functional Use of XR in the Presentation of DH

The essential feature of XR devices is to perceive their surroundings and respond to them. Smartphones and tablets perceive their surroundings thanks to computer vision. A user of a “marker-based” AR application uses a built-in camera in the device to search for visual markers and image segments predefined in the application code. The application performs a predefined operation when the XR device recognises such a mark. There are many options for what can happen next. The performed action can link to a web address, as in the case of a QR code reader, and display additional written information describing the object targeted by the camera. The application can then start an audio or video recording. Recognition of the code mark may initiate the launch of any other mobile application function. For example, after reading the code, the XR device can determine its local position and start navigating in AR to the selected destination or another point of interest.

In the following paragraphs, we will focus on individual cases of the use of computer vision in XR devices and demonstrate how to use the functionality of AR applications to achieve the desired intention of the curator in creating an exhibition.

The listed examples are a result of an extensive search in common academic databases including Web of Science, Scopus, Google Scholar, IEEE Explore, and the ACM Digital Library. There are also examples of XR exhibitions found on public media (New York Times, The Guardian, etc.) and also XR exhibitions visited by the authors of article in person.

The database search criteria were set as follows:

- Scientific publications from the year 2018 (on March 2018, AR was provided for general public use through the release of ARCore, a software development kit developed by Google for Android smartphones; on September 2017, Apple launched AR support on their devices via the toolkit ARKit);
- Search rule for keywords: augmented reality OR virtual reality OR mixed reality OR extended reality AND digital heritage OR interactive exhibition OR immersive experience.

Publications with detailed description of XR applications for DH exhibition were selected for deeper analysis. Each selected example represents the key features of XR technology in a specific way and tries to suggest how a well-made exhibition with incorporated XR elements could look. The examples should serve as a pattern for XR exhibition creators, from curators to IT specialists, as a starting point for their imagination and inspiration for their visions about future exhibitions.

5.1. The Immersive Experience

An immersive experience (IE) pulls a viewer into another real or imagined world. The combination of visual and sound technology delivers unforgettable and engaging worlds. The implementation of VR headsets or AR devices is not necessary to create an IE. Some special exhibitions display 360° video animations with a system of wall projectors. Compared to other XR technologies, viewers are allowed minimal interaction with the

content. However, the advantage is the comfort of the viewer, as you do not need to put on a headset or hold an AR device in your hand. All you have to do is sit on the couch in a specially designed room with 360° projection, relax, and be absorbed by the presented content (Figure 5). Presenting the exhibits using 3D-walk-through and panoramic views is more effective than traditional brochures and static information desks to attract the minds of visitors [22]. Spectators can experience such an IE in a series of exhibitions of artists such as Claude Monet, Klimt, or Van Gogh curated around the world.



Figure 5. Klimt—The Immersive Experience, animated immersive exhibition, Vienna, Austria.

5.2. AR system Based on AR Marker Recognition

Nowadays, a widespread functional feature of AR applications is to perform a pre-defined action in the code after recognising a specific marker or so-called “AR tag” [23]. The fundamental principles of AR application are described by Mullen in the book “Prototyping Augmented Reality” [24]. In the basic form of AR applications, we know them as QR code readers on mobile devices. After deciphering the QR code, the mobile application will display a hyperlink to the destination web address on the device display. On the display of the device, the QR code is enriched, augmented with additional information and a hypertext link, which is digitally generated on the surface of the QR code (Figure 6a). For the purpose of presentation and visualisation of digital heritage, AR applications are designed to display additional textual information for the relevant item at the museum exhibition on the surface of the AR marker (Figure 6b) or visualise a 3D model (Figure 6c).

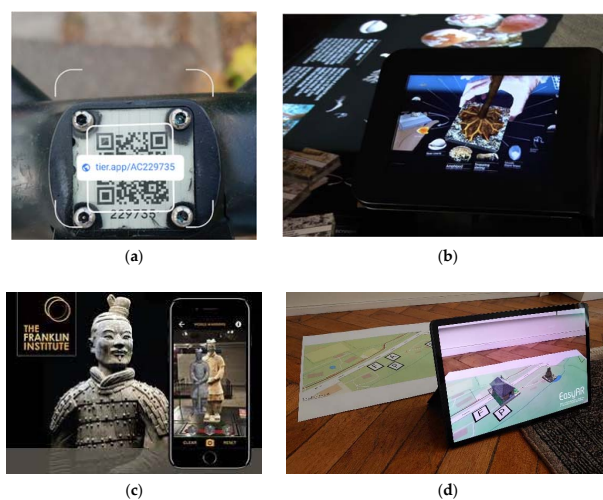


Figure 6. Visually based AR applications. (a) QR code augmented with a hypertext link; (b) display of additional descriptive information on the exhibit at the Paleontological Exhibition, Auckland War Memorial Museum, New Zealand (source ²); (c) extension of the Terracotta Army exhibition with 3D sculpture models in AR, Franklin Institute, Philadelphia, USA (source ³); (d) augmented area plan of the area of the Wallachian Muse in Nature, Rožnov, Czech Republic.

As part of the project to visualise the Wallachian Open Air Museum in Rožnov, we implemented an augmented plan of the museum complex (Figure 6d), in which we incorporated AR tags [25]. After scanning the tag using a mobile device, the application generates a 3D model of the object located in the specified location. After selecting an object on the display of the mobile device, additional information will be displayed for the chosen object.

Three-dimensional models are usually displayed in a static state. If the creative team also has an experienced graphic designer, it is possible to set static models in motion with the help of animations. Dynamic elements enliven and energise the presentation experience (Figure 7).



Figure 7. Animated butterflies on a wall painted with graffiti. AR application in Philadelphia Insectarium, Yetzer Studio (source ⁴).

5.3. User-Defined Placement of Digital Objects in Space

The visual display of AR information is not limited to image marker recognition. Reality can be enriched by user-selected elements from the application library. In the case of digital heritage, a suitable example is the visualisation of a 3D model of a selected object. Using an AR application, an XR device maps the surface of surrounding objects in the real world and detects planar surfaces, horizontal or vertical (Figure 8). On the display of the device, the user selects the spot on the flat surface where they want to place the selected 3D model. The user is able to interact with the selected 3D model—rotate, change its position by shifting over the planar surface, resize the model, run animation, or display additional information. Current technologies allow visualising detailed 3D models composed of tens of thousands of polygons (Figure 9). The advantage of using the AR tag lies in the user's freedom to place the 3D model anywhere. It is not limited by the physical features of the AR marker—its size, shape, or material.



Figure 8. Visualisation of a planar surface via an AR device in an AR application represented by dark texture with a grid.



Figure 9. AR placement of 3D models freely in space.

5.4. Enhancement of the Surface with Digital Elements

An AR application is not limited to displaying only one object at a specific location, referenced by an AR tag, or at a user-defined location. When an AR application defines planar areas of the real environment using XR device sensors, the application can continue to work with these areas. They can be covered with texture or randomly generated 3D models. In this way, the AR can cover the user's surroundings with snow cover, submerge the user into a tropical storm, or create a desert landscape around the user. A practical example is an application visualising to the visitors of an open-air museum specific plants blooming on local meadows in a specific season of the year (Figure 10).



Figure 10. Enhancement of planar surface with grass texture and randomly generated 3D plant models. AR demonstration of flora during a different season.

5.5. Puzzle in XR

According to Kyriakou [26], the most popular creative activities for museum visitors include exhibits encouraging visitors to a specific challenge. Participation in the challenge will examine and develop their logical, visual, and creative thinking. A good example is a puzzle-solving task—assembling a broken or disassembled object. The physical contact of visitors with the exhibit is unacceptable due to the historical value of the exhibited objects. Current technologies make it possible to replicate the exhibit using 3D printing, thus allowing visitors to interact with a copy of the object. However, this approach also has its limitations. Only one visitor has access to the object at a time, manipulation may damage the replica, or it may be “lost”. In the case of jigsaw puzzles, assembling complex 3D models from individual parts may not be possible without glue. XR provides all the

tools needed to complete a 2D or 3D puzzle task. Executing a task in the application code is simple. When the edges of the two puzzle pieces approach each other at the right angle, they join like magnets. In the Unity engine, verification of the mutual position of two objects is simply executed by using “raycasts”, imaginary vectors originating in a point on the object’s surface, emitted under a certain angle with a range of a defined distance. Subsequently, the application code verifies whether the sent “raycast” hit the searched area of the adjacent puzzle piece (Figure 11a). If so, the two pieces of the puzzle will fit together. From a programming perspective, VR and AR applications are very close to each other. From the perspective of the application functionality, the interactive task of assembling the puzzle can be similarly incorporated into augmented and virtual reality. The only difference is how the control system is programmed (Figure 11b). For AR, we are still limited to entering instructions via touch on the display surface of the XR device. Application control and manipulation with objects in VR are realised using dedicated XR controllers. Gradually, the number of VR applications with integrated control by sensing the movement of the hands and signalling specific gestures with the fingers on the hand is increasing [27]. The number of motion and ambient sensors incorporated in VR headsets is gradually increasing, and their quality is improving. This leads to more precise sensing of the user’s movement, focusing specifically on finger gesture movement [28] and more detailed sensing of the environment. Technological progress enables the successive shift of some VR applications to the level of MR, where the user interacts simultaneously with virtual objects in a real environment [29].



Figure 11. XR puzzle. (a) Matching AR puzzle using colour-defined “raycasts” solved by manual flipping and spinning of AR tags, Unity engine; (b) VR puzzle solved by 3D spatial movement of puzzle elements using VR controllers, Batman Arkham VR.

5.6. Digital Reconstruction of the Object

Reconstruction of a damaged object (Figure 12) is a time-consuming and costly process. The virtual environment and XR tools provide excellent capabilities for virtual object reconstruction. The application of digital reconstruction can be seen in the reconstruction of small artifacts [30] and their missing parts and the restoration of entire buildings [31], even entire ancient cities [32]. This process saves time and money. Sometimes it can be the only way to revive a damaged or destroyed object, especially if the original construction process of the object is not known, the original material for restoration is not available, or a change in the ideology of the local population no longer wants the physical restoration of the destroyed object. However, it requires good communication between an experienced digital graphic designer and an expert on the history of the reconstructed object. Close cooperation of specialists in their field will ensure that the digital reconstruction of the building is technically, factually, historically, and visually correct [33].

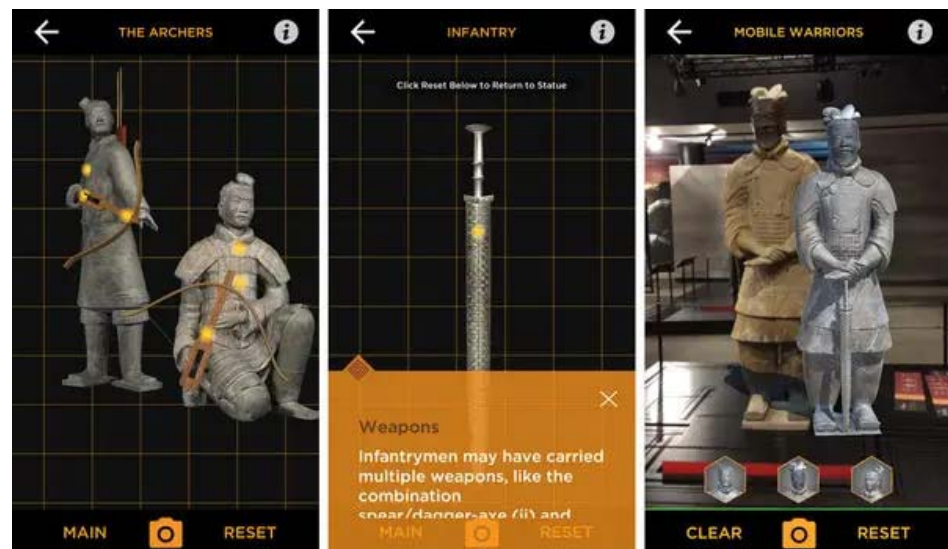


Figure 12. Digital reconstruction of missing—disintegrated—parts of terracotta warrior statues, including additional text information, Franklin Institute, Philadelphia, USA (source [5](#)).

Digitally reconstructed objects will subsequently also find application in digital archaeology (cyber-archaeology) in simulations of events that took place in the past [\[34\]](#). Three-dimensional models can also be used in software analysis in archaeology [\[35\]](#).

5.7. Narrative Storytelling

XR has the necessary functions for creating complex multimedia exhibitions that retell the history of a given locality or object, namely through visual communication, written text, and soundtrack. Liestøl [\[36,37\]](#) describes in his publications AR applications simulating historical events that took place at a given place. With the help of AR, mobile devices in the hands of tourists become smart guides, telling stories from the past on device displays (Figure [13](#)).



Figure 13. AR reconstruction of a naval battle in the port of Phalasarna, Greece [\[37\]](#).

5.8. Mixed Reality, the Realistic AR

Specific XR devices are designed to project digital content such as 3D objects, video, and images into a real environment. Devices using advanced optical technology for displaying 3D computer-generated images on the lens, the transparent display of smart glasses (such as Google Glass, Magic Leap, Microsoft HoloLens), are available on the market. Although the Microsoft HoloLens device is marketed as an MR device, many researchers and professionals are still reserved about this label, and given its current capabilities are leaning towards the label AR or realistic AR [\[19\]](#). The main reason for this label is the 3D computer-generated imagery content on the lens, the device's display, and not its holographic projection onto the real environment, as well as the low degree of interaction between the digital content and the real environment. The difference between mobile AR

and an AR headset is hidden in the possibilities of tracking the movement of the whole body; while using the headset, the hands are not engaged [38]. The unoccupied hands and wider field of view of headset provide a more immersive experience compared to the use of mobile AR [39]. In addition, the conceptual solution of the headset allows a variety of sensorial input, such as eye tracking, tracking of hand movements, entering commands with hand gestures, or voice control.

A valuable example of the use of realistic AR technology in the field of CH is the dramaturgical performance Sutton House Stories. Dima created a 4 min AR experience capturing the lives of the residents of Sutton House, a Tudor mansion in the London Borough of Hackney (UK). While passing through the house interior, the viewer is accompanied by three voices, the key residents of the house, who lived there over the course of four centuries. In addition, while listening to voices narrating their life events, the viewer watches the animated AR visual content (Figure 14).



Figure 14. Sutton House Stories, realistic AR experience by Dima [40].

At certain moments, there is an opportunity for interaction, even if it is not explicitly suggested to the viewer. For example, when the viewer watches a pair of dancing ballet shoes while listening to orchestral music, some of the audience spontaneously began to copy the steps of the shoes and danced alongside. Afterwards, they described feeling “as if the whole house came to life” [40].

The Microsoft Hololens device is helping to create similar immersive experiences combining the real world and DH more and more often. Another specific example is the activity of the French creative studio SAOLA, which creates realistic AR content for the National Museum of Natural History in Paris. During the currently ongoing exhibition REVIVRE—“To live again” (autumn 2022), museum visitors are accompanied on the tour by animated prehistoric creatures in AR (Figure 15).

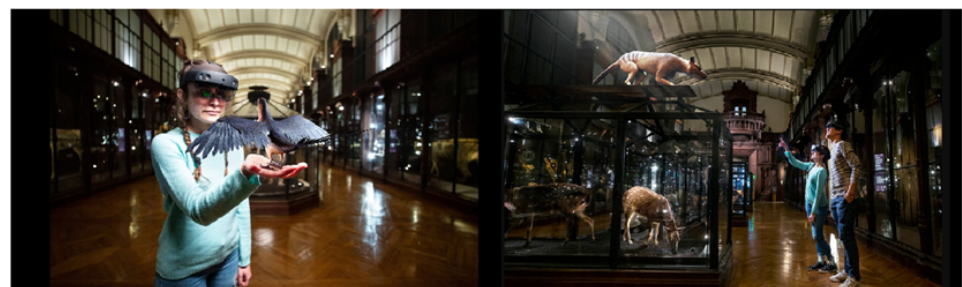


Figure 15. REVIVRE (“To live again”), realistic AR exhibition designed by SAOLA Studio, National Museum of Natural History, Paris, France (source 6).

5.9. Virtual Museums

The concept of a virtual museum makes it possible to share the presented information without the need to tie the exhibited objects to a certain place and time. In the following lines, we will present four virtual museum concepts. Each of them has a specific approach to space—where and how to present content, what to present and for whom. As a first example, we will present the exhibition No Spectators: The Art of Burning Man, realized by the Smithsonian Institution in the Renwick Gallery, Washington, DC, USA. The

aim of the exhibition was to present to the visitors contemporary works of art already once presented to the public during the Burning Man festival (Figure 16a). Burning Man is a specific festival. Many artworks exhibited are burned during the festival. This underlines the spirit and the main principles of the festival: to forget the past and let things go (“non-attachment and letting go”), to live for the present, to be free (“as a gesture of freedom”), and not to leave any traces behind (after the end of the festival). However, a few artworks from the festival were chosen by the artists to be retained for re-exhibition at the Renwick Gallery (Figure 16b). Gallery visitors were also able to learn about the origins of the event and understand the spirit of the festival. Unfortunately, this exhibition was also limited in time. It ended in January 2019. The works were digitised via photogrammetry and laser scanning and are still available to the public in the virtual tour No Spectators on VR platform Sansar (Figure 16c). People still do have the opportunity to see the exhibition, even though the physical collection no longer exists. Additionally, it is accessible to visitors from the comfort of their home. That is one of the benefits of VR. Thanks to VR, we can create and share lasting records of otherwise temporary experiences.

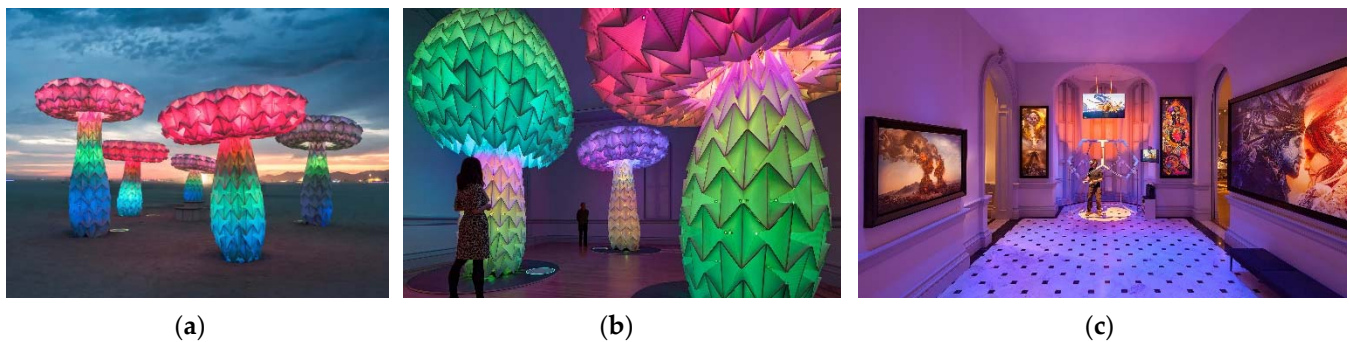


Figure 16. Burning Man. (a) Shrumen Lumen, an interactive art installation of huge origami mushrooms, 2016, Burning Man, Black Rock Desert, Nevada, USA (photo by Rene Smith); (b) re-exhibition of art installation (2018) in the Renwick Gallery, Washington, DC, USA (source ⁷); (c) No Spectators, virtual museum experience on Sansar platform (source ⁸).

A different approach to presenting DH was taken by the Kremer Museum (Figure 17a). It is an innovative concept, combining modern VR technology and a classic collection of paintings by old masters from the Dutch Golden Age. The museum premises were created and exist only in digital form [41]. The museum is designed in a futuristic style. Kremer’s collection contains a collection of 74 paintings by Danish and Flemish artists (Rembrandt, Aelbert Cuyp, Frans Hals), which was created by the creative studio Moyosa Media. Digital images were created photogrammetrically, thus capturing their digital original in high resolution. A similar concept of a VR museum was also documented by Ardhiati at the Soekarno’s Painting Collection Series [42]. The Soekarno Virtual Art Gallery is designed in the shape of a white lotus, reflecting the expectations of millennials for modern architecture. The creators of the gallery concept try to draw the attention of virtual visitors with the contrast created by the combination of modern VR museum technology and classical art [43].

London’s Victoria and Albert Museum opened the “Curious Alice” exhibition in the summer of 2021, looking at the origins, adaptations, and rediscovery of Lewis Carroll’s classic work. Alongside the exhibition of illustrations, films, and manuscripts, visitors had the chance to immerse themselves in an interactive VR experience. VR is an ideal tool for entering a fantasy world such as Wonderland, where Lewis Carroll’s original illustrations come to life without having to obey the laws and theories of classical physics (Figure 17b). It is a concept of a virtual world, a fictional world conceived and designed virtually, following the scientific laws defined only by the game engine and in the code written by the programmers.

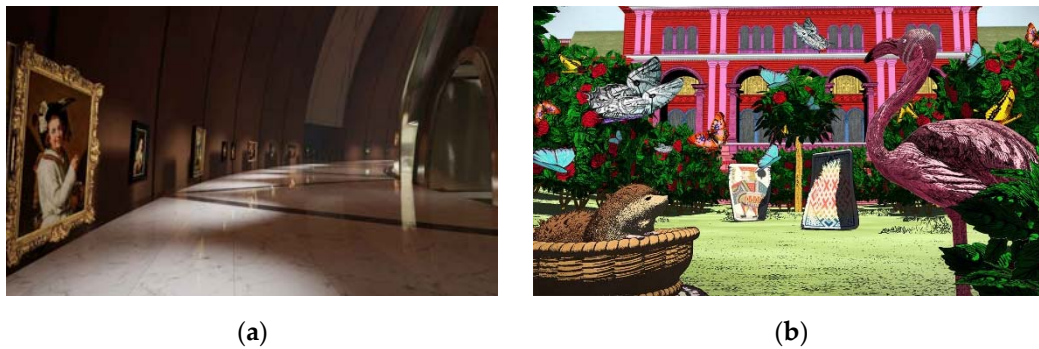


Figure 17. (a) The Kremer Museum innovative concept of a virtual museum, VR collection of old masters' paintings (source ⁹); (b) Curious Alice, immersive experience in fantasy world Wonderland, V&A Museum, London, UK (source ¹⁰).

Another approach to creating a virtual tour is the digitisation of the real environment and objects using photogrammetry and laser scanning. A visitor to this type of VR museum can also visit remote places that may otherwise be inaccessible (mobility problems, effort to reduce the carbon footprint caused by travelling, entering a dangerous location, etc.). As an example, we will present a virtual tour of the Alistrati cave. The tour of the cave is enriched by the commentary of the guide, a levitating robotic companion, accompanying the visitor on the way through the cave [44]. Photogrammetry in combination with XR technology has also proven itself as a suitable method for documenting the seabed and communicating the results to the public [45]. Through the VR museum Underwater Malta, visitors can dive into the inaccessible depths of the oceans and discover captured historical objects on its bottom, sunken ships, planes, and other submerged objects (Figure 18).

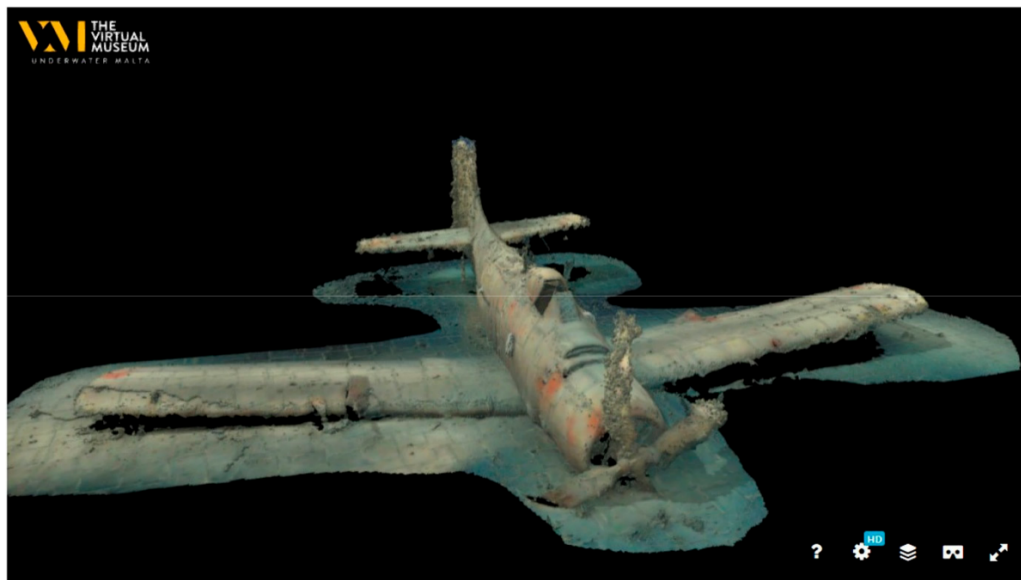


Figure 18. The Virtual Museum—Underwater Malta, 3D model of a sunken aircraft discovered on the seabed [45].

6. Evaluation of the Methodologies of Creating XR Applications in CH

If we would like to classify and evaluate XR applications for CH, the first criteria should be the quality and origin of the presented data. How was the 3D model displayed by the XR application created? Is it the result of artistic reconstruction or partial or complete reconstruction based on defined construction blueprints, or is it an authentic digital replica of the original object made via photogrammetry and laser scanning? Each of these DH creation procedures has its own justification and purpose [46]. From a technical point of

view, accurate documentation of the object via photogrammetry and laser scanning brings the most reliable and realistic results. However, it is not always possible to apply this method. Each of these methodological approaches has its application and target audience, as we demonstrated with the examples in Section 4. The evaluation of the quality of the presented content is based on the assessment of the metadata of the XR application, as well as what tools and software were used in the creation of digital content, and the source of additional descriptive information (textual or audio-visual). In the case of telling a story [47], is the story based on scientific research or historical documents, or is it based on fables and legends, or is it a fictional story? These stories can mediate connections between tangible and intangible heritage [48]. Although we observe an effort to modify individual elements of the application in order to attract attention and create a sensation, the historical fidelity of the content, especially for the purpose of presenting CH, should be preserved.

From an economic point of view, the success of an XR application can be compared not only based on the number of users and visitors it reached and interested, or the number of museums and galleries that decided to include the XR application in their program, but also the number of investors who were so impressed by the XR application that they decided to support its further development [49]. XR is a powerful media tool. However, it should not be forgotten that XR's goal for CH is to include XR in museum and gallery exhibitions. They should be created with an effort to follow their main ideas, educate and stimulate the curiosity of visitors, make them think, and encourage future research and creative activities.

7. Discourse on the Current State of Virtual Heritage

A lot of research has been performed evaluating the meaning, importance, and purpose of interactions between interactive exhibitions and information technology. Whether the research is older, conducted around the year 2000 [50–53], or current [51–56], the researchers come to common conclusions. Visitors of museums and galleries evaluate multimedia exhibitions positively. Exhibitions enriched with information technologies are especially sought after by the young generation (students, school trips). The application of XR has considerable potential in the field of education. As reported by Bacca et al. [57], the implementation of XR as a complementary method in the education process expands the amount of information that students are able to learn, increases their motivation to acquire new knowledge, strengthens their ability to cooperate, and, at the same time, is a low-cost teaching aid—almost all students have their own smartphone, where they are able to install the XR application. Educational exhibitions are also becoming a reality thanks to the cooperation of the public sector with researchers [58–60].

However, new technologies are not the exclusive concern of the young population. As time goes on, there is a generational change. In the middle-aged and older population, a group of people is gradually growing who love modern technologies and are able to make full use of and take benefit from the potential of dynamic and interactive exhibitions in museums and galleries [61].

Museums strive to engage the widest possible range of the public, but successful exhibitions should be created with regard to the target audience. If the exhibition is targeted to a certain group of people, it is important to choose a suitable communication style for the target audience [62]. Through her research, Pallud points out how the mutual interaction between the exhibition and the visitor influences emotional processes, stimulates curiosity, and supports analytic skills [63].

Although the scientific public has been dealing with the topic of creating multimedia exhibitions for several decades, thanks to advances in technological development, the possibilities for creating an exhibition continue to advance. At present, there is a predominant effort to create mobile applications and transfer part of the content from the multimedia panels in the museum to smartphones and tablets, which are operated by the users themselves

during the exhibition tour [64]. An essential component of the interaction is intuitiveness. Otherwise, the user is discouraged as a result of encountering a dysfunctional exhibit.

Some curators are worried that XR is shifting the potential visitors from museums back to their homes. On contrary, the vast majority of virtual heritage researchers believe that their work encourages people to visit a real site, to sense the *genius loci* in situ [65]. Their products transform passive spectators into active users of multimedia applications, providing them with added information that enriches the visit to a real site. This consideration is still in its infancy. Until virtual heritage technologies become a widely used tool, there is still time to discuss their proper focus and direction. Devices supporting XR and related applications are becoming more and more affordable, not only in terms of price and performance but also in terms of their functionality. They are already available today not only to institutions with a high budget but also to smaller organisations and individuals. Ultimately, the XR compatible device, the smartphone, is carried by everyone almost all the time, everywhere. This makes it possible to significantly reduce the budget when creating an exhibition. It is enough to create or modify an existing mobile application for the needs of the new exhibition and transfer it to the visitor's mobile device, smartphone, or tablet. This eliminates the cost for the museum or gallery to purchase hardware to deliver the XR experience.

If we briefly take a look at the situation regarding VR, the use of VR has continued to grow significantly in recent years. An affordable Oculus Quest mobile VR headset from Meta is popular within the user community. However, it is mostly used only by individuals for their domestic needs. Its mass deployment in museums and galleries has not yet seen high numbers. On the one hand, its launch was slowed down by the global chip shortage, which in 2020 significantly reduced the availability of the Quest VR headset shortly after its launch. In addition, the shared use of the headset in public places is still socially unacceptable in post-pandemic times. The development of VR content for the needs of the museum remains a matter of debate [66].

Even this fact did not discourage developers, who continue to create quality VR applications for the purposes of virtual tourism and the presentation of digital heritage in the virtual world [44].

If the question is whether to use AR or VR, Bekele [67] concludes AR is the most suitable technology for enriching and deepening the experience of the exhibition. AR and MR can be best used in applications focused on the reconstruction of historic buildings intended for interior and exterior exhibitions. VR is a suitable for entering the world of virtual museums.

Economou [68], at the end of her research on multimedia applications in museums, correctly points to the need for close cooperation between content creation specialists, programme designers, and educators in the creation of multimedia exhibitions. The IT sector should only assist in creating the content. Leadership in content creation should be left to the museum and the humanities. The key to success is to understand the cycle of cooperation does not have a starting and ending point. It changes and evolves over time. Each project requires a specific approach [69].

After analysis of the reviewed articles, we suggest the curator of exhibition should discuss the full potential and possibilities of XR technologies for DH presentation purposes with IT specialists.

Sadly, we encountered, during the review process, many cases where the visitor is set into a role of a passive viewer watching a pre-recorded video sequence with not many possibilities of interaction between the presented content and the visitor. We consider this a poor XR integration. Luckily, we were able to discover some well-made XR applications, their qualities appreciated by the users, public media and professional reviewers. Some of these XR applications we presented in this review article. We hope the chosen examples enrich the XR knowledge of our readers and inspire them to develop interesting XR projects.

A user-friendly interface and simple control should be taken into account in the development of XR applications. We suggest to XR developers always to integrate a guide or

a short tutorial manual with control instructions. If XR should attract visitors to exhibitions and XR technology becomes successful, the key is the quality of XR applications presented to the public during museum and gallery exhibitions.

In general, XR provides just a visual experience at the moment. Further, we expect the expansion of XR's capabilities in the area of haptic feedback interaction especially [70,71]. The research activities aim to solve the problem of haptic feedback with different technologies, including electromagnets (TacTiles), electro stimulation (Teslasuit, OWO), and micro-motors (HaptX), with the most promising technology using pneumatic (DextrES) or hydraulic principles (Meta's VR Gloves). Some of the haptic gloves (Weart) are able to mediate the sensation of touching hot or cold surfaces. Replacing VR controllers with haptic gloves will lead to a change in the locomotion system in VR applications, changing button interaction to hand gesture commands and opening the world of VR to visually impaired users. When the prototypes and enterprise-targeted haptic devices are accessible to the masses, the XR experience will become even more immersive.

XR brings benefits for the visually impaired. An adapted mobile application can scale the size of the read text to their needs, and the text can be supplemented with an audio recording. XR expands the possibilities of the interaction with the users by incorporating voice control. The possibilities of XR allow it to be used for medical purposes as well. XR's capabilities suggest a wide range of uses, for example treatment of post-traumatic and stress disorders (e.g., a virtual walk through a castle park accompanied by relaxing music); treatment of claustrophobia (gradual increase in difficulty when exploring closed and cramped spaces, catacombs); treatment in the field of memory training (coincidence with well-known art objects and landmarks, displaying information in language mutations); and fear of heights (virtual walk through a monument at a height). XR makes inaccessible locations for people with limited mobility (wheelchair, crutches) accessible [72]. XR allows for immobile people to overcome distances to virtually travel to selected locations, to discover places where they could not otherwise go.

Virtual tourism can draw attention to inaccessible, forgotten, or little-known monuments, thus expanding the possibilities for receiving grants and founding for their upkeep or restoration.

8. Conclusions

The extension of the traditional exhibition in a museum with the possibilities of XR adds a dynamic dimension to the static exhibition, where the user of the application is able to interact with objects in a virtual environment. With the help of XR, it is possible to enrich the exhibition with elements that cannot be integrated into the exhibition because of physical limitations.

The integration of extended reality does not intend to replace the traditional exposition in the museum with new technologies nor to move visitors to a virtual metaverse. On the contrary, new approaches to information and communication technology provide the exhibition curator with a multi-purpose tool for creating dynamic interactive exhibitions.

Publishing this article, we hope not just to provide curators with a broader insight into XR possibilities, but also to inspire researchers to reach out for further cooperation with museums and galleries as an opportunity to exhibit, test, and demonstrate their research results.

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Notes

- ¹ Wallachian Open Air Museum: <https://www.nmvp.cz/en/roznov> (accessed on 25 October 2022).
- ² Auckland War Memorial Museum: <https://www.aucklandmuseum.com/> (accessed on 25 October 2022).
- ³ Franklin Institute: <https://www.fi.edu/> (accessed on 27 October 2022).
- ⁴ Yetzer Studio: <https://www.yetzerstudio.com/> (accessed on 27 October 2022).
- ⁵ New York Times: <https://www.nytimes.com/> (accessed on 27 October 2022).
- ⁶ SAOLA Studio: <https://www.saolastudio.com/en-gb> (accessed on 7 November 2022).
- ⁷ Smithsonian Institution: <https://www.si.edu/> (accessed on 25 November 2022).
- ⁸ Sansar: <https://www.sansar.com/> (accessed on 24 November 2022).
- ⁹ The Kremer Museum: <https://www.thekremercollection.com/> (accessed on 23 November 2022).
- ¹⁰ Victoria and Albert Museum: <https://www.vam.ac.uk/> (accessed on 23 November 2022).

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