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X-reality technologies for museums: a comparative evaluation based on presence and visitors experience through user studies

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Abstract

Virtual museum systems, based on different X-reality technologies, has begun to spread, as they represent decisive tools to promote exhibitions and reaching out to audiences. Although budgetary considerations have so far limited the choice of technologies a wide range of possible technological options are available today at low cost. This paper provides the results of an empirical study, with the aim to determine the most appropriate technologies to satisfy the visitors' expectation and maximise their likelihood to repeat and recommend the experience. The study focuses on the comparison of the performance of five VM systems for visualise digital reproduction of archaeological finds, based on different technologies (i.e., PC desktop, holographic display, 3D stereoscopic projection, head mounted display and mobile Augmented Reality). The results provide useful insight for the development of VM systems, in order to maximize the visitor experience in terms of *presence* and ability to activate an *experience economy* perspective.

1 Introduction

In the last thirty years, the emergence of the so-called "new museology" philosophy [1] has led to a progressive but radical change in the relationship between museums, societies and communities. Visitors acquired a growing centrality in their relationship with museums, becoming fundamental interlocutors for what concerns their fruition [2]. As a result, modern museums have extended their mission not only to educate, but to manage cultural heritage in the more open, inclusive and creative way, by offering educational content to visitors in a playful way, and emotionally involve them. Staging remarkable experiences also represents a profitable way to respond to the need to expand the audience and to increase ticket sales and museum sustainability [3]. To this end, new Interaction and Communication technologies (ICT) represent decisive tools to promote exhibitions, to drastically change the way they are conceived and organised and reaching out to audiences.

Among available technologies, during the last decade museum institutions demonstrated a great interest in the so-called X-Reality (XR) technologies, given their strong appeal and the potentialities they offer to both improve cultural heritage fruition and attract visitors. These technologies allow to manipulate the reality by enabling the connection between physical and cyber environments in different proportions. Based on the "Reality-Virtuality Continuum" proposed by Milgram and Kishino [4] they can be classified in: Virtual Reality (VR), Augmented Reality (AR), Augmented Virtuality (AV) and Mixed Reality (MR). Virtual Reality (VR), when fully exploited, completely immerses the users in a synthetic environment, entirely computer-generated [5]. AR enhance reality by adding spatially aligned computer-generated information (e.g., 3D models, textual annotations) on the user’s real surrounding, using special display technologies [6]. AV augments the virtual world by superimposing real-world live scenes on virtual environments [7]. MR is characterised by the total blend of virtual elements (e.g., holograms or projections) with the real world, so that users can interact in the same time with both digital and real contents [8]. An increasing number of virtual museum systems (VM) have been proposed in the last years [9], to enhance traditional collections and exhibits with modern technological systems. Over the years, several studies demonstrated the viability of various systems based on VR, AR and MR for different application areas in CH (e.g., [9] [10] [11] [12] [13]), while AV did not seem to have aroused any interest.

The quality of 3D graphics and the characteristics of adopted interaction and visualization technologies in general determine the user’s involvement with the resulted x-reality environment and consequently affect the user's subjective experience during the interaction with VM [14] [15]. Immersion represents the technological factors that mainly affect user involvement in XR environments and determining the “sense of presence” [16]. Immersion can be defined as the degree to which a system can reproduce natural perception and action through multisensory displays, tracking [17], so that is strictly dependent on the XR technology's ability to provide sensory stimulation and interactivity.

XR systems can be classified as non-immersive, semi-immersive and immersive, based on the level of immersion they provide [18]. Nowadays, the most widely used VM still use non-immersive visualization systems, e.g., 2D PC monitors with desktop control devices for interaction or 2D multitouch displays [19]. Semi-immersive systems exploiting visualization technologies more like large-screen movie experiences (e.g. toroidal projection, stereoscopic powerwall projection, videowall, holographic projection) are also quite often adopted, as these systems enable to accommodate many visitors simultaneously [9] [20]. However, such system usually adopt interaction systems not intended for multiple users, e.g. handheld devices, gesture interfaces [21], while there is minimal adoption of fully immersive virtual reality (VR) and augmented reality (AR) [20] [22].

Budgetary considerations that have constrained the choice of technologies by museums may explain this occurrence [22]. Nevertheless, today several XR technologies are available at low cost, characterised by various supporting devices, user workspace, and different levels of immersion, interaction, and presence.

Given this wide range of possible technological options, it is imperative to have assessment methods that allow to objectively compare the various possible technological set-ups, in order to identify the solution more suitable to meet the experiences desired by visitors.

To achieve this goal one possible way is to investigate how the characteristics of the available technologies may enhance visitors' VM experience, in order to enable an "experience economy" perspective [23].

With this aim, in the past years, a growing number of studies examining the effectiveness of XR technologies in improving visitors' experience at museum, cultural heritage sites and art galleries. For example, Sylaiou et al. [24] analysed the relationship between presence and enjoyment in VR virtual museum, and between object presence and enjoyment in AR virtual museum. Jung et al. [25] analysed the effect of a mixed VM environment (VR & AR) on the visitor experience. He et al. [12] examine the impact of information type (dynamic verbal vs. dynamic visual cues) and augmenting immersive scenes (high vs. low virtual presence) on visitors' evaluation of the AR museum experience.

Despite the growing literature of experimental studies on the topic, there is no systematic literature review or metanalysis focusing on an evidence-based comparative assessment of the various technologies to facilitate operators in choosing the best installation for their goals. The existing studies cannot be easily compared, as they focus on different assessment objectives, different technologies, and different application contexts (i.e., art gallery, cultural heritage site, archaeological museum).

At the best of our knowledge, only Barbieri et al. [22] reports a comparative evaluation of different VM through user studies. However, they mainly considered system interface usability as a criterion for comparison. Insofar, no study proposed empirical approaches to perform a comparative evaluation of alternative XR technological set-ups in order to determine the best technological specifications based on the user-perceived overall interaction quality, and on the resulting visitors' museum experience, considered in terms of the Pine & Gilmore's four experience economy realms [23].

2 Research aim

This paper reports the results of an empirical research based on user studies, for the comparative evaluation of VM systems, based on different XR technologies. The aim is to provide useful insights for selecting the most appropriate technologies for a specific application context.

The proposed evaluation approach focuses on the assessment of:

- The user's sense of presence experienced during the interaction with XR Technologies;
- The quality of the provided museum experience;
- The visitors' attitude towards the experience and their likelihood of repeating and recommending it.

The assessment hinges upon the following hypotheses:

H1: Greater quality of the visitors' experience increases its emotional valence and corresponds to greater Attitude towards the experience (ATE).

H2: Greater presence corresponds to greater ATE.

In addition to the direct effect of the VM experience on visitors' evaluations, experience it is likely to mediate the relationship between presence and these evaluations. In other words, as stated in [24], greater presence corresponds to greater visitors' evaluations, but this is an indirect effect at least partially explained by the fact that presence, as a subjective psychological response, increases the experience valence and therefore influence the visitors' ATE. In fact, [26] suggests the importance of presence as mediating variable between the media experience and the emotions induced by it.

H3: Experience mediates the effect of presence on ATE

3 Material and methods

This paper proposes an empirical approach for the comparative evaluation of VM systems, based on user perceptions, using different XR technologies. To establish the internal and external validity of the comparative study, the following steps are described in detail below: the definition of the experimental design, the choice of the theoretical constructs to be measured, the establishment of a measurement procedure, and the statistical methods used in the analysis.

3.1 Experimental Design

This study used a single-factor within-subject design in order to examine the impact of the VM technological setup on the visitors' experience, presence and overall attitude towards the experience. The five levels of the single-factor "VM technological setup" were:

- Three VR systems based on different technologies: 2D desktop, 3D active stereoscopic projection, and head mounted display (HMD);
- A mobile Augmented Reality (AR) system;
- A MR system based on holographic projection.

The choice of suitable technological setups is generally performed by museum managers taking into account both the requirements related to the context of implementation and budgetary constraints [22]. Consequently, different systems that respond to the museum's needs (i.e., costs, market availability and integrability) are taken into consideration. All enable visitors to visualise and interact with digital reproductions of archaeological finds, whenever the actual artefacts cannot be physically exposed to the public. Among the five VM systems considered, four of them are already widely used in museum. The last one is based on a new low-cost holographic technology that so far it has been used mainly in the retail sector to display products and advertising, although it could be suitable also for museums. The first system adopts 2D pc monitor for the visualization and pc mouse for interaction/navigation. Such system is widely used, primarily for Web-based virtual museum. The second system is based on active stereoscopic projection realised via a projector F10 AS3D ZOOM by Projection Design on a front-projected flexible display (150" DIAMOND; 300x225 cm). To visualise the projection in 3D, users need to wear special glasses (in our study, we used active glasses by NuVision). The third system consists of a fully immersive VR system based on a HMD; in our implementation, we used HTC VIVE with two VIVE base stations. The fourth system consists of a mobile AR application. Users can visualise in full scale the virtual reproduction of the artefact on a smartphone with a 2246 x 1080 6.18" FHD+ display, by framing the marker with the camera. The marker is posed on a pedestal.

Finally, an MR environment is considered: it exploits a new holographic technology based on an LED display projector fan (i.e., HYPERVSN SOLO L), which creates the illusion of an airborne hologram and a sense of three-dimensionality of the object. This amazing effect is created by a high-speed spinning LED light bar, making the hardware structure virtually invisible, and a video floating effect.

For each technological system, a proper SW application has been developed in Unity 3D by Unity Technologies, according to the building settings required by the considered x-reality technologies (Figure 1).

Each SW application allowed the user to examine the digital reproductions of three archaeological finds – i.e. the Augusto Capite Velato, the Dagger and the attic Kylix (Figure 2) – currently exhibited in the Museo Archeologico Nazionale delle Marche of Ancona, and to interact with them according to the technological set-ups as shown in

Figure *3*.

In particular, the desktop application allows the user to: (1) rotate, (2) pan and (3) zoom the digital object, respectively by: (1) clicking and dragging the left mouse button, (2) by holding the mouse wheel and dragging and (3) by rolling the mouse wheel. The application for stereo projection enables user interaction with the artefact (i.e. rotation, pan and zoom) through a touch-screen console. Previous studies evidenced that this kind of interaction technology resulted in the most usable one in a museum context [22]. The fully immersive VR application was developed by using the SteamVR plugin. User interaction is realised thanks to the HTC VIVE tracking system, which allows visitors to interact with the environment in a completely natural way: the system acquires the position and orientation in space of the HTC VIVE headset worn by the user and consequently adjusts in real time the position and orientation of the camera view used to allow the virtual environment to be displayed. The real and virtual space are mapped 1:1. In this way, while users are moving in the real space, they see the perspective of the virtual environment changing coherently, so that they have the impression that they really are in the virtual environment, and that they can approach and move around the artefact, just like they could in the real world.

The AR application was developed by using Vuforia Engine. It enables the user to view the object from any angle, by moving around, approaching and moving away from the marker using a smartphone. The application for the holographic projector consists of video rendering of digital reproductions made in Unity. This technology does not allow any kind of interaction between the user and the object, but it reproduces the experience of seeing an object rotating in a display case.

As the VM system aims in general to improve the exhibition and therefore the fruition of cultural artefacts [9], each application was developed in order to maximise the perception of digital cultural artefacts. To this end, in order to focus the visitor's attention on the digital reconstruction, the environment design results absolutely minimal (i.e. the object is presented in a total black environment). The considered digital models have been built by using the most recent digitalization technologies [27] and are characterised by a very high level of accuracy.

3.2 Theoretical constructs

3.2.1 Presence

Whenever the interaction with objects, or environment, is mediated by communication technology, users are forced to perceive simultaneously two separate environments: on the one hand, the physical environment in which they actually are, and on the other hand, the digital environment presented through the technology. To refer to the overall subjective experience with the computer-generated environment, scholars usually adopted the concept of “presence”.

In the context of VR environments, “presence” is usually defined as “the subjective experience of being in one place or environment, even when one is physically situated in another” ([28]: p. 225). This definition of “presence” seems to apply well for full-immersive VR systems, characterised by displays that surround and isolate a user from the real world [29]. However, this definition does not seem easy to apply to other kinds of realities, as AR and MR. In fact, augmented and mixed environments elicit a different kind of “presence”: they convey the impression that virtual objects are present in the real environment, rather than transport or immerse the user in another environment. In these contexts, it is more useful to consider presence as a “perceptual illusion of non-mediation” ([30], p. 2), or as an experience in which the individual does not notice “the para-authenticity of mediated objects” or “the artificiality of simulated objects” ([31]: p. 36). Such definitions do not distinguish between real and virtual objects or environments, so that they apply for every kind of realities. Consequently, in this research, according to [32], we do not distinguish between presence and telepresence.

Presence is a subjective psychological response, it is individual and context-dependent: it depends on the user’s mental imagery [15] and user’s ability to isolate itself by events that result from outside of the virtual environment [28]. Scholars agree that the assessment of a user’s presence judgement is one of the main usability criteria of VEs systems [33]. Moreover, the notion of presence has been widely used in understanding consumers' attitudes and future behavioural intentions in various AR and VR contexts [5]. The most common method of measuring presence is post-experiments selfreport based on standardised questionnaires [34]. In particular, Witmer & Singer's [28] Presence Questionnaire (PQ) is the most widely used scale, even if it has been defined to assess presence in immersive virtual environments. Many authors have defined new questionnaires/scales, readjusting the PQ, in order to compare the level of presence in environments characterised by different levels of immersion (e.g., [32] [35]).

3.2.2 Experience economy of Virtual Museums

The term "Experience Economy" was coined by Pine & Gilmore [23], to describe a new business opportunity typical of a service economy, based not only on the sale of products and services, but on the enrichment of products or services through the offer of a "memorable experience". To move forward into the experience economy, today's museums should focus on visitors and visitor experience, rather than focusing on collection and marketing campaigns to increase visitor numbers and broaden the target audience: they should stage experiences that meet the visitor desires [36]. Several studies have highlighted the strong effect of experience on visitors' behavioural intentions in terms of likelihood of repeating and recommending the visit [3] [25] [37]. According to Pine & Gilmore [23], to achieve this objective, the experience must include a combination of experience realms: education, entertainment, escape and aesthetics.

X-reality technologies can be effectively used to create a VM experience that encompasses all these aspects: they may facilitate the learning experience, satisfy new entertainment expectations, enhance the aesthetic experience and contribute to the escaping of reality [25]. However, several studies found that technology characteristics and VM design elements strongly affect the museum visitor experience. For example, He et al. [12] examined different AR-based VM design alternatives and found that solutions that provide a high level of presence offer a better aesthetic experience. Pallaud [38] and tom Dieck et al [39] observed that perceived technology interactivity strongly affects components of visitor experience related to the edutainment realm. Consequently, the choice of the enabling technology must depend on the application context and on the experience that the considered application is intended to provide. For example, augmented reality seems to be preferable for exhibition enhancement, while virtual reality seems better for virtual museums [20].

However, very few studies (i.e., [24] [40]) reported comparative analyses of the effective performances of VM based on different x-reality technologies. Only Jung et al. [25] examined the impact of a VM environment on visitor experience applying experience economy theory. No studies proposed comparative assessment methodologies to understand how VM design solutions, based on different x-reality technologies, determine different visitors experience, considering the Pine and Gilmore's [23] four realms of experience.

3.2.3 Attitude towards the Virtual Museum Experience

A VM experience could be positive or negative. The (emotional) valence of the experience will reflect in either positive or negative (cognitive) evaluation by the visitor, which will also be more prone to repeat and recommend the experience. Moore [41] establishes a comprehensive measure of Attitude Towards the Experience (ATE) to evaluate the valence of hedonic experiences, i.e. those experiences that are chosen for pleasure and are affective and sensory in nature, in contrast with utilitarian experiences that are goal-oriented and cognitive in nature [42]. A VM experience falls under the former category.

No studies have used a comprehensive measure of VM experience to investigate visitors' attitudes in relation to the type of X-Reality technology used for the VM experience.

3.3 Measurement

The theoretical constructs described above were measured by adapting reliable scales proposed by previous literature (Table *1*). A total of three scales have been used.

The first one refers to the measure of Presence (PR) and is adapted from Yim et al. [32]. It is composed by seven 5-point Likert-type items anchored at the end points “not at all” = 1 and “absolutely” = 5.

The second scale aims to capture the quality of Visitors Experience (VX) in terms of the Pine & Gilmors’s [23] four experience realms. It consists of 16 statements adapted from Radden & Han [3] and Jung et al. [25]: 4 related to education realm (EDU), 4 to entertainment (ENT), 4 to escapism (ESC) and 4 to aesthetics (EST). All items are rated from 1 (strongly disagree) to 7 (strongly agree) by using 7-point Likert scales.

The last scale measures the visitors’ Attitude Toward Experience (ATE) in terms of valence and likelihood of repeating and recommending the visit. It has been adapted from Moore [41]. It includes four 7-point Likert-type items with bipolar verbal anchors to measure the overall valence of the experience and two statements, rated from 1 (not at all) and 7 (absolutely) to assess the visitors’ attitude toward the experience in terms of intention to revisit and to recommend.

Figure *4* provides a graphical illustration of the evaluation model. The diagram uses symbols from the McArdle-McDonald reticular action model [43]:

a. Latent variables (constructs/scales), i.e. variables that are not directly observed but measured by a set of items or by other subscales, are represented with ellipses;
b. Observed variables (Measurement Items or indicators) are represented by abbreviations (e.g. Edu1, Edu2, etc. represent the measurement items of the latent variable Education);
c. Hypothesized direct effects of one variable on another are indicated with arrows (e.g. →)

The lines described in (c) that points from a latent variable to an indicator represent the presumed causal effect of the latent variable on the observed scores. Statistical estimates of these direct effects are called factor loadings, and they are generally interpreted as regression coefficients. As in all regressions, direct effects are measured with measurement errors. For parsimony we omit in the model diagram the error terms.

The model in Figure 4 also has a structural component that depicts the direct and indirect causal effects among latent variables (e.g. Presence causes Experience, while Experience causes ATE; indirectly, Presence causes ATE via Experience, but a direct link may also be hypothesises and tested). Statistical estimates of these effects are called path coefficients. The latent variables that are caused by other latent variables are called *endogenous* (i.e. Experience and ATE). Statistical errors of these endogenous paths reflect only omitted causes and not also measurement error.

3.4 Data collection

The actual experiment consisted in asking an experimental subject to ‘experience’ all the three artefacts described above by each of the five selected XR technologies. To avoid carry-over effects, the order in which the technologies were presented to the subjects was counterbalanced across participants. After having experienced each XR technology, participants were asked to fill in questionnaires reflecting the measures previously described.

A total of 30 voluntary subjects (11 females and 19 males), aged between 18 and 56 (Mean = 32, SD = 10.26), without particular visual acuity problems, have been recruited among students from the engineering faculty and personnel of the “Department of Industrial Engineering and Mathematical Science” (DIISM) and the “Department of Agricultural, Food and Environmental Sciences” (D3A) of the Università Politecnica delle Marche. The number of participants has been chosen considering the minimal sample suggested for statistical analysis [44] [45]. Participation to the study was encouraged by the opportunity to win one of two Amazon vouchers, valued 10€ each, by a lottery draw among all participants. The participants to the experiment received informed consent previous to accessing the lab.

3.5 Statistical methods

After testing the scales for reliability, repeated-measure ANOVA was performed on the data to test for main effects of the technology levels using SPSS. The choice to refers to the mean instead to the median is because the median of a Likert scale is going to be very inefficient at showing differences between groups. In fact, parametric tests (e.g., t-test) has been shown to work better on Likert scales than non-parametric tests (e.g, Mann-Whitney-Wilcoxon) in several studies (e.g., [46], [47]).

Estimation of the Confirmatory Factor Analysis (CFA) and Structural Equation models was performed using a robust (Satorra–Bentler) maximum likelihood estimator [48] [49] using Mplus 8 [50].

A post-hoc analysis was conducted to assess invariance of the model across the various technological conditions of the VM experience, too. For all the tests, the significance level was set to 5%.

4 Results and discussion

Scores related to PR, VX and respective dimensions (i.e., EDU, ENT, ESC and EST), and to ATE were calculated by averaging the respective item values per participant. Internal consistency of all the scores was high (Cronbach's on the pooled values: PR, $\alpha = .88$; VX, $\alpha = .95$; EDU, $\alpha = .91$; ENT, $\alpha = .87$; ESC, $\alpha = .81$; EST, $\alpha = .89$; ATE, $\alpha = .97$).

Figure *5* reports the results of presence with the considered VM systems. Repeated-measure ANOVA with technologies (holographic projection, desktop, AR, stereoscopic projection and HMD) as within-subjects factor and PR as dependent variable revealed a highly significant main effect of technologies, $F(4, 116) = 33.29$, $p < .001$. Considering the desktop-based system (M = 3.13, SD = 0.88) as a bases for comparison (i.e., the cheapest technology and more widely used technology), repeated-measures t-tests (Bonferroni-corrected) evidenced that presence with HMD (M = 4.24, SD = 0.44) is significantly higher, difference = -1.114, $t(29) = -8.050$, $p < .01$, while it is significantly lower with the holographic projection (M = 2.70, SD = 0.87), difference = 0.419, $t(29) = 3.094$, $p < .05$. There are no significant differences between desktop and AR (M = 3.51, SD = 0.62) and between desktop and stereoscopic projection (M = 3.55, SD = 0.80).

The fact that the holographic system does not allow the user to interact with the artefacts, except as a spectator, may explain these findings. Instead, the systems based on desktop, mobile AR and stereoscopic projection, allow the visitors to perceive the artefacts and interact with them in different ways. The desktop system, characterized by a hi-resolution monitor, allows visitors to appreciate the artefacts in the finest details. The stereoscopic projection maximizes the spatial perception of the artefacts. The mobile AR system allows visitors to observe the actual dimensions of the artefacts and naturally interact with them. However, all these systems use external devices (i.e., monitor, smartphone, projected wall), so that the perception of interposed technology between the user and the artefact is high and this limits the illusion of non-mediated interaction. On the contrary, the system based on HMD (i.e., a wearable device) is the only one that allows the visitor to experience a perceptive illusion of non-mediation effectively.

Results related to the overall VX are reported in Figure *6*. Repeated-measures ANOVA evidences an high significant effect of technology on VX, $F(4, 116) = 22.926$, $p < .001$. As it can be observed, the experience with HMD (M = 5.56, SD = 0.76) resulted the most appreciated, while that provided by holographic projection (M = 3.44, SD = 1.26) was judged as the less satisfying. Repeated-measures t-tests (Bonferroni-corrected) shows that experience with AR (M= 4.41, SD = 0.78) is significantly more satisfying than holographic projection, difference = 0.967, $t(29) = 4.013$, $p < 0.01$. Stereoscopic projection (M = 4.63, SD = 1.35) is significantly less satisfying than HMD, difference = -0.935, $t(29) = -4.060$, $p < 0.01$. Neither AR differed significantly from stereo projection nor desktop from holographic projection.

Repeated-measures ANOVAs were performed to evaluate visitor experience also at the subscale level. Figure *7* reports the mean values of VX subscale across technologies

Results evidenced a significant effect of the technology on EDU, $F(4, 116) = 14.307$, $p < .001$, on ENT, $F(4, 116) = 24.203$, $p < .001$, on ESC, $F(4, 116) = 21.044$, $p < .001$, and on EST, $F(3.121,$

90.504) = 15.945, *p* < .001 (in this last case, the Mauchly's test was significant, so a Greenhouse-Geisser's correction has been used).

Repeated-measures t-tests (Bonferroni-corrected) evidenced that HMD-based system maximised the visitor judgments regarding all the VX dimensions. In particular, regarding the EDU dimension, the system based on stereoscopic projection (M = 4.84, SD = 1.47) performed significantly worse than the HMD (M = 5.55, SD = 1.06), difference = -0.717, t(29) = -3.273, p < 0.05. The stereo-based system performed significantly better then holographic projection (M = 3.68, SD = 1.60), difference = 1.150, t(29) = 3.905, p < 0.01. There are no significant differences between the systems based on stereo projection, desktop (M = 4.47, SD = 1.46) and AR (M = 4.69, SD = 1.60).

Regarding the ENT dimension, AR (M = 4.92, SD = 1.01) performed significantly worse than HMD (M = 6.08, SD = 0.75), difference = -1.158, t(29) = -6.421, p < 0.01, but resulted significantly better than desktop (M = 3.80, SD = 1.65), difference = 1.117, t(29) = -3.581, p < 0.05. Neither AR differed significantly from stereo projection (M = 4.82, SD = 1.48) nor desktop from holographic projection (M = 3.77, SD = 1.33).

Regarding the ESC dimension, the system based on stereoscopic projection (M = 3.92, SD = 1.52) performed significantly worse than the HMD (M = 4.90, SD = 1.44), difference = -0.992, t(29) = -3.434, p < 0.05, but significantly better then desktop (M = 2.98, SD = 1.32), difference = 0.933, t(29) = 3.623, p < 0.05. There are no significant differences between the systems based on desktop, AR (M = 3.11, SD = 0.95) and holographic projection (M = 2.71, SD = 1.20).

Finally, regarding the EST dimension, there is a significant difference between the performances of systems based on HMD (M = 5.70, SD = 0.75) and stereo projection (M = 4.93, SD = 1.50), difference = 0.767, t(29) = 3.155, p < 0.05. Holographic projection (M = 3.60, SD = 1.58) performed significantly worse than stereo, difference = -1.333, t(29) = -3.730, p < 0.01. There are no significant differences between the systems based on stereo projection, desktop (M = 4.18, SD = 1.59) and AR (M = 4.89, SD = 0.88).

Figure *8* shows the results related to respondents' ATE with the considered technologies. Repeated-measures ANOVA revealed a highly significant main effect of technologies on ATE, *F*(4, 116) = 16.56, *p* < .001. The experience with HMD-based system (*M* = 6.50, *SD* = 0.51) is significantly more appreciated by visitors than desktop (M = 4.79, SD = 1.56), difference = -1.712, t(29) = -5.929, p < .01 (Bonferroni-corrected). The experience with holographic projection (M = 4.15, SD = 1.71) resulted significantly less captivating than AR (M = 5.51, SD = 1.05), differences = -1.360, t(29) = -3.862, p < 0.01 (Bonferroni-corrected), and stereo, differences = -1.232, t(29) = -3.298, p < 0.05 (Bonferroni-corrected). No significant differences were found between desktop, stereoscopic projection (M = 5.38, SD = 1.43) and AR.

To test the hypotheses referring to the relationships among the latent variables, we specified and estimated the structural equation model represented in Figure *4* by Partial Least Squares Path Modelling (PLS-PM). Since a mediational model is a causal model [51], H3 is tested by predicting that the direct effect between presence and attitude towards the VM experience is not statistically significant. A two-step approach was used, allowing a second order factor structure for the VX scale.

The first order factor loadings of the measurement model are reported in Figure 9.

The results are quite robust, showing an average R-squared of 0.78, while all path coefficients are statistically significant i.e. with P-values below 0.05 (Figure 10). The loadings are all above 0.7 with the exclusion of three items, two related to different subscales of VX and one to Presence (not reported in the figure for parsimony). Variance Inflation Factors (VIFs) are all below the recommended threshold of 5 [52], suggesting that multicollinearity is not an issue in our data. The values of Rho-A and Average Variance Extracted (AVE) for each latent variable indicate a good discriminant validity of the model (

Table *2*).

Global pooled estimation (across all technologies) confirm H1, H2, and H3, showing partial mediation. The indirect effect calculated by Sobel method is 0.779 (SD: 0.048), while the total effect is (0.210+0.779=0.989): 78.8% of the total effect of PR on ATE is explained (mediated) by VX.

Figure *11* reports the results of repeating the analysis by technology. The estimated structural parameters were calculated by bootstrapping (200 replications) for each technology; for each relationship, the first bar always reports the value of the global pooled estimation, followed by the technology-specific parameter values.

For what concerns the relationship between VX and ATE, VX experience positively impact ATE for all technologies. However, HMD and especially holographic projection exhibit a significantly lower structural parameter than AR (base technology). The relationship between PR and ATE is the most homogeneous across technologies, since only holographic projection significantly differs from others, with a much higher direct impact of Presence on ATE. The relationship between PR and VX is the most heterogeneous, with all technologies but HMD exhibiting higher impact of Presence on VX than AR and HMD. Overall, the null hypothesis that the structural path coefficients of the different technologies are all equal is rejected.

The results of our multi-technology analysis suggest that, besides being scaled in terms of all the latent variable measurement (with holographic projection exhibiting the lowest scores for all the three metrics and HMD the highest), the different technologies impact on ATE with somewhat different mechanisms. For example, holographic projection has the highest direct effect of PR on ATE (0.528) which is more than double the average global effect (0.210) and almost ten times as much than AR (0.77). Stereoscopic PR even impact on ATE with a negative sign.

By inspecting Figure *11*, we can conclude that for all technology ATE is mostly explained by VX, either via its direct effect on ATE or the (mediated) indirect effect of PR. Only for holographic projection, PR explains ATE more than does VX, especially if one considers that PR path coefficient to VX is the highest in absolute value (0.921).

5 Conclusion

X-Reality technologies are widespread tools in the field of cultural heritage and play an important role in attracting new visitors, eliciting amazing experiences and maximising their likelihood to repeat and recommend the experience. To guide the selection of technological solution more suitable to meet the experiences desired by visitors in the context of archaeological VM, this study compared the performance of five XR technologies (i.e., PC desktop, holographic display, 3D stereoscopic projection, HMD, Augmented Reality), in terms of on PR, quality of VX, concerning the experience economy dimensions, and visitors' ATE.

The study provides some theoretical results: it confirms that both presence and VX are antecedents of ATE: in general, ATE is mostly explained by VX, either via its direct effect or a mediated effect of PR, as evidenced by previous studies (e.g., [5] [25]). However, results suggested that different technologies impact on ATE with somewhat different mechanisms (e.g., Stereoscopic PR impact on ATE with a negative sign, holographic projection PR explains ATE more than does VX). Future studies should be carried out to better understand the nature of such mechanisms and analyse how other specific technological features, which this study neglected, may affect the relationship between PR, VX and ATE.

This study provides also practical implications, as results suggested that the proposed method can provide indication to support decision making within a VM design process. In particular, where XR technologies are used to visualize digital reproduction of archeological finds, HMD allows to maximize all four VX dimensions (e.g. EDU, ENT, ESC, EST), while holographic projector has proved to be the least suitable technology to enable an "experience economy" perspective in museums. There are no significant differences between desktop, AR and stereoscopic projection in terms of VX quality provided with respect to EDU and EST dimensions. However, the desktop provides a lower quality experience level for the ENT dimension than AR and Stereoscopic projection, while Stereoscopic projection results in better quality experience than desktop and AR regarding the ESC dimension. Overall, HMD provides a significant better performance in terms of ATE then desktop, while holographic display performs significantly worse. No significant differences have been found between desktop, stereoscopic projection and AR.

These results provide useful insight for the development of VM systems in the context of Archaeological Museums. Even if, as is well known, HMD has the limit of being a single-user technology, and therefore its applicability may be limited by logistical and budget reasons, it seems to be the first choice technology to maximise the interest and satisfaction of visitors (especially young people), arousing in them memorable experiences, and to encourage them to repeat the experience. When contextual constraints require you to choose multiple-user technologies, Stereoscopic projection or application based on mobile AR can be considered good solutions in order to maximize the visitor experience in terms of *presence* and ability to activate an *experience economy* perspective, while desktop-based systems are not as attractive, and holographic display does not seem to be a suitable technology.

Nevertheless, the present study has some limitations. First, the experiment has been conducted in a laboratory environment. The quality of the experience that can be aroused by technology in a real museum context can therefore be different. Future studies should assess the real effect of XR technologies on visitor experience in a real museum context. Moreover, this study focuses on XR technology performance in a specific application context: the visualization of digital reproductions of archaeological finds. Future studies are needed to compare VM systems performances, to determine which is most suitable to maximise the quality of the experience in other application contexts. Furthermore, all the participants involved in the study had good attitude and skill with PC technologies and most of them have previous experience with several XR technologies. Future studies must be carried out to assess how the user technology skill may affect ATE and VX with XR technologies.

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Caption for figures

Figure 1. Development of VM system applications.

Figure 2. The digital reproduction of the considered Archaeological artefacts. From left to right: the Augusto Capite Velato, the Dagger and the attic Kylix.

Figure 3. The considered VM applications.

Figure 4. The hypothesised model.

Figure 5. Mean values of Presence by technology.

Figure 6. Mean values of Visitor Experience (VX) by technology.

Figure 7. Radar chart of mean values of VX subscale across technologies.

Figure 8. Mean values of ATE by technology.

Figure 9. First order factor loadings (0.7 lines indicate the usual threshold used for significance).

Figure 10. Results of PLS-PM (Obs. 150; average R—squared 0.78; average communality 0.73) (coefficient P-values in brackets).

Figure 11. Structural parameters by technology.
Note: Within each relationship, bars without "a" indicate parameters that are significantly different than the AR parameter (P-value<0.05)

Table 1.Measurement model

	Item
Presence	**How completely were all your sensed engaged?**
	How much did the visual aspects of the objects involve you?
	How compelling was your sense of objects moving through space?
	How much did your experience in the virtual environment seem consistent with your real-world experiences?
	How compelling was our sense of moving around the objects?
	How closely were you able to examine objects?
	How involved were you in the virtual experience?
Visitor Experience	***Education***
	The overall experience stimulates my curiosity.
	The overall experience has increased my desire to know more about the artefact.
	This experience has increased my interest to the details of the object.
	I learned something about the artefact from this experience.
	Entertainment
	I would like to repeat this experience.
	This experience stimulated me emotionally.
	During the experience I had fun.
	This experience was unusual.
	Escapism
	I have lost the track of time.
	I have lost track of where I was.
	I have escaped from reality.
	I felt that I don't was interacting with the artefact.
	Aesthetics
	This experience was better than the one I could have with the real object.
	Experimenting this technology was enjoyable.
	The virtual artefact was attractive.
	The virtual technology was attractive.
Attitude Toward Experience	**Good / Bad**
	Appealing / Unappealing
	Positive / Negative
	Liked / Disliked
	What is the likelihood of you repeating the virtual museum experience?
	What is the recommending the virtual museum experience to others?

Note. For each scale, the order of items has been randomized

Table 2. Measurement model evaluation

Variable	AVE	Rho-A	VIF : ATE	VIF : VX
Presence (PR)	0.608	0.923	4.887	1.000
Experience (VX)	0.786	0.931	4.887	-
ATE	0.834	0.964	-	-