Comparing Virtual and Augmented Reality Applications for Museums: User Immersion and Learning Performance

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This study investigates the impact of Augmented Reality and Virtual Reality technologies on User Immersion and Learning Performance in museum settings. A quasi-experimental study, conducted in the context of an archaeological virtual museum, compares the effects of AR and VR interfaces on User Immersion and Learning Performance. Participants (n = 176) interacted with digital replicas of archaeological artefacts via AR and VR interfaces, followed by assessments using the Augmented Reality Immersion (ARI) questionnaire and knowledge-based multiple-choice tests. The use of the ARI questionnaire made possible a comprehensive investigation of the effect of User Immersion (and not only some of its aspects, e.g., Presence or Flow) on Learning Performance in the context of Cultural Heritage. The results revealed that AR users achieved higher Learning Performance, while VR users experienced a greater immersive experience. Significant correlations were found between higher User Immersion levels and lower Learning Performance. These findings highlight the importance for Museum curators to find a balance between exploiting technology to entertain and maintaining the educational integrity of the exhibits.

CCS Concepts: • **Human-centered computing → HCI theory, concepts and models**;

Additional Key Words and Phrases: Augmented Reality, Virtual Reality, Learning Performance, Immersion

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1 Introduction

Museums, as defined by the International Council of Museums (2007), are public institutions that engage in the acquisition, conservation, research, communication, and exhibition of humanity's tangible and intangible heritage for educational, study, and enjoyment purposes.

Over the years, museum learning has been highlighted for its ability to enhance interest and cognitive skills, allowing visitors to appreciate historical artefacts, to learn about various disciplines, and to respect diverse cultures [1, 2]. Despite the educational benefits, in the last decade, attendance and interest in museums, especially among the younger generation, have begun to decline. This has led to calls for creating more engaging learning experiences to rekindle visitor interest [3]. As a consequence, in recent years Museums started to exploit **eXtended Reality Technologies (XRTs)** as a mean to increase museums accessibility and comprehensibility [4, 5], improving edutainment [6, 7], providing engaging and immersive narratives, boosting museums' attractiveness and visitors' attitude toward the visit [8] and even enabling visitors' profiling [9, 10].

In particular, **Virtual Reality (VR)** and **Augmented Reality (AR)** technologies are becoming more prevalent in museum educational programs, with the goal of making learning experiences more interactive and captivating [8, 11–15]. Both technologies hold significant promise for educational applications in museums: they have the potential to transform passive observation into interactive and engaging experiences. By simulating historical contexts and providing interactive elements, these technologies can enhance cognitive engagement, making the learning process more effective and memorable. Particularly interesting is the work by Spallone et al. [16], where they showcase a methodology to implement an AR app with an animated avatar in order to produce a digital storytelling to support the fruition of the Museum of Oriental Art's of Turin, Italy. Their aim is to include different ages, schooling, and cultures population as well as people with sensory and cognitive disabilities [17]. Zhang et al. [18], similar to Oladokun et al. [19], propose a framework to develop a broad Cultural Heritage metaverse, including XRTs, which can serve multiple purposes (e.g., tourism guidance, site maintenance, conservation).

VR is capable of offering a fully immersive experience by creating a completely synthetic environment that can transport visitors to different places or eras, providing an unparalleled sense of presence. In contrast, Mobile AR overlays digital information onto the real world, allowing users to interact with their physical surroundings in enriched and novel ways.

When a museum exploits highly immersive technological devices, the advantages of AR and VR reach their maximum expression [20], as they stimulate visitors' senses more naturally and vividly, helping to enhance the quality of the experience and the educational effect of the visit [21].

User Immersion is a fundamental aspect in the fruition of digital content in **Virtual Museums (VMs)** [22, 23]. It can be defined as "the participant's suspension of disbelief that she or he is 'inside' a digitally enhanced setting" [24]. As evidenced in [25], User Immersion is crucial for knowledge acquisition and visitor satisfaction, enhancing both the efficiency and effectiveness of learning. Additionally, it contributes to a relaxed and enjoyable state, further enriching the overall museum experience.

AR and VR applications fundamentally differ in their approaches to User Immersion and interaction: while VR aims to create a high level of User Immersion by isolating users from the real world, AR maintains a connection to the user's actual surroundings, integrating digital elements into the physical space.

The varying levels of User Immersion provided by AR and VR can significantly influence the effectiveness of each technology in facilitating learning [26]. Therefore, understanding how User Immersion with AR and VR applications impacts the museum learning experience is crucial. This knowledge can assist museum curators and educators in designing more impactful and educational exhibits, ultimately enriching the visitor experience and fostering a greater appreciation of cultural heritage. The choice of integrating AR and VR applications should be aimed at enhancing the enjoyment of educational content, ensuring that visitors leave the museum with a greater understanding and appreciation of the material, since the primary goal of visiting a museum is to gain detailed information about the exhibits, such as historical artefacts, artworks, scientific samples and cultural relics, and to develop a deeper understanding of the material presented [11]. This educational mission must remain a priority, even as museums increasingly aim to attract and entertain visitors with new technologies, so that it is essential to strike a balance between using technology to entertain and maintaining the educational integrity of the exhibits. This is crucial nowadays, as several low-cost XRTs are available, characterized by different supporting devices and different levels of User Immersion and interaction. Immersive XRTs demonstrated their benefits on learning in several contexts, such as English teaching and learning [27], college-level physics teaching [28], or generic higher education contexts [29].

Despite the growing interest in AR and VR for museum education, prior studies have primarily focused on isolated aspects of the user experience (e.g., Presence, enjoyment, or usability), often comparing different technologies in different application domains or against desktop systems and without adopting a comprehensive, theory-driven measure of User Immersion (e.g., [30–35]).

Moreover, existing comparative works do not examine how the multi-level structure of User Immersion (i.e., Engagement, Engrossment, and Total Immersion) influences objective Learning Performance within the same cultural experience.

Beyond reporting differences in learning outcomes and immersion between AR and VR, this work contributes novel evidence on the complex relationship between multi-level User Immersion and Learning Performance in museum contexts. By combining a theory-driven immersion measure (ARI) with objective knowledge tests and an ecologically valid quasi-experimental design, our study shows that higher Total Immersion and Engrossment can coexist with reduced learning, whereas Engagement, driven by Interest and Usability, supports learning.

In this context, this article aims at contributing to fill this research gap. It reports the results of a quasi-experimental study, conducted in the context of an archaeological VM, that focuses on the comparative evaluation of two **User Interfaces (UIs)** of a VM system, respectively based on VR and AR technologies, in terms of User Immersion and resulting Learning Performance.

The rest of the article is structured as follows: Section 2 presents the Research Background and a deeper insight into User Immersion and Learning Performance assessment. Section 3 describes the Methodology, detailing the characteristics of the AR and VR UIs considered, the experimental setup and procedure, the considered measures, the collected data, and the statistical methods. Subsequently, Section 4 illustrates the results obtained and discusses them. Finally, Section 5 draws the conclusions and highlights limitations and potential future works.

2 Research Background

This section delves into the concepts of User Immersion and Learning Performance, providing the definitions of the two concepts adopted in this article.

2.1 User Immersion

User Immersion is a term frequently used in research concerning AR and VR and should not be confused with Presence or Flow [36], which instead constitute two of the foundational elements of User Immersion. Over the years, various definitions have been attributed to this term, mainly stemming from two perspectives: the first one considers User Immersion a technical, objective, and measurable aspect of the technology system used during an experience, described as *the ability to deceive a person's senses by providing them with a simulated reality perceived as real* [37–39]. The second perspective instead considers User Immersion as a psychological state that occurs when a person interacts with a stimulating environment [40]. Both perspectives, however, envisage that User Immersion is mediated by some form of interaction technology. A third perspective, more commonly employed among others in the digital game field, views User Immersion as a possible natural state of the human being, capable of emerging whenever the person engages in a compelling activity [41]. According to this definition, listening to an opera, reading a novel, or playing a video game can induce User Immersion in the individual.

When comparing a museum experience in its AR and VR variants, a measurement of User Immersion could be adopted. Despite this, in the literature, there are various examples of comparisons between different versions (i.e., AR, VR, and desktop) of the same experience (in the field of Cultural Heritage and beyond), but rarely is the comparison made through the level of User Immersion, more often, it only considers Presence. Ghoshal et al. [30] compared the AR and VR versions of a co-located multiplayer online video game. The experiment focused on comparing Presence and Co-Presence through the relative items of the questionnaire found in [31], along with Game Enjoyment (via the Game Enjoyment Scale [42]) and Cybersickness. Furthermore, the paper is not focused on the field of Cultural Heritage. Aslan et al. [32] focused on comparing the Presence (through the Presence Questionnaire [40]) and Workload induced by an AR app using three different devices (a smartphone, a tablet, and a head-mounted display), while Dow et al. [33] also compared Engagement. In these two cases as well, the experiences were not related to Cultural Heritage and lacked a VR version of the experience (i.e., only AR in [32] and AR vs. desktop in [33]). Loizides et al. [34], in the field of Cultural Heritage, compared two VR versions (presented via a head-mounted display and a stereoscopic Powerwall) of museums focusing on Cypriot Cultural Heritage and Art, only comparing Presence and Usability through a generic questionnaire developed by the authors. Finally, Verhulst et al. [35] carried out a comparative analysis between the AR and VR versions of a cultural experience considering the parameters of Presence (through the Igroup Presence Questionnaire [43]), Enjoyment (through a 5-point Likert single-item questionnaire), and Engagement (with a combination of self-developed items and already validated questionnaires), conducting the study with real museum visitors while also analyzing negative side effects, although without analyzing User Immersion.

The papers discussed so far predominantly measured Presence while looking for User Immersion. Nevertheless, as theorized by Cheng et al. [23] User Immersion can be considered as a hierarchical and multi-level structure with three constructs, each containing multiple subscales, with Presence being one of such subscales. The first construct is Engagement: if the user perceives the activity as interesting and stimulating (Interest) and perceives good usability of the technological media (Usability), the level of Engagement increases. The second construct, Engrossment, occurs when the user begins to develop an emotional attachment to the activity (Emotional Attachment) and starts to focus on it (Focus of Attention). Finally, when the user feels the sensation of being surrounded by a virtual environment (Presence) and is totally absorbed in the activity (Flow), the psychological state they are in is that of Total Immersion. To measure User Immersion according to this theoretical model, we adopted the **Augmented Reality Immersion (ARI)** questionnaire [44], which measures User Immersion through 21 items, and it is structured according to the theoretical model [23, 45]. The ARI questionnaire, therefore, assigns a score to six different scales (e.g., Interest, Usability, Emotional Attachment, Focus of Attention, Presence, and Flow) and through them, provides a measure of the three constructs of User Immersion (Engagement, Engrossment, and Total immersion). The ARI questionnaire is a valuable tool for measuring User Immersion in both AR and VR applications.

While earlier research suggested that achieving a sense of presence in AR is more challenging compared to VR due to the differing levels of immersion [46, 47], recent advancements in XRTs have begun to bridge this gap. Modern XR systems now facilitate a more refined conceptualization of presence, distinguishing between Cognitive Presence, i.e., the user's psychological engagement and intentionality, and Perceptual Presence, i.e., the sensory integration of virtual elements within the real environment. This dual-faceted approach acknowledges that presence is not solely dependent on technological immersion but also on the user's cognitive and emotional engagement with the experience. For instance, Triberti et al. [48] argue that presence is fundamentally a psychological phenomenon shaped by narrative context, individual user characteristics, and intentional structures, rather than merely by technological sophistication. Similarly, Hameed and Perkis [49] emphasize the importance of coherence and congruence in virtual environments, suggesting that the believability and authenticity of an experience significantly influence the user's sense of presence. Recognizing these dimensions, the developers of the ARI questionnaire have shifted focus from measuring presence in isolation to assessing User Immersion more holistically. This approach allows for a more accurate measurement and comparison of user experiences across both AR and VR environments, accounting for the complex interplay between technological, cognitive, and perceptual factors.

Finally, unlike other examples found in literature, such as the Immersive Experiences Questionnaire [50], Immersion in Game Narrative [51], and the Game Immersion Questionnaire [23], the ARI questionnaire was developed specifically for AR applications rather than desktop-based applications [44] and could also be employed for VR applications [52, 53].

2.2 Learning Performance

Learning Performance can be defined in various ways. For example, it can refer to students' test scores, their satisfaction with the learning experience, or even their activity and achievements recorded in an online learning system [54]. The Learning Performance can be defined as the achievement of a learning activity in a given situation [55]. It is generally measured through the assessment of cognitive outcomes such as knowledge recall and application, retention and problem solving [56].

Based on the results of research, highly immersive and interactive XR environments seem to benefit both knowledge understanding and skills development [57, 58]. XRTs make learning more visual, enable users to be activated, and more fully engage them in the learning process [59]. Moreover, they facilitate students' engagement in appropriate cognitive processes and improve emotions and motivation [60] so that they can learn better and, thus, positively affect their academic success [61]. The usefulness of XR in education might also depend on the type of learning. XR potentially allows all three learning styles, i.e., visual–auditory–kinesthetic [62] to be targeted in one application. However, activities performed in XR, especially in immersive VR, can result also in an increase of cognitive work [63]. This can be attributed to the predominantly cognitive nature of activities performed in XR environments, as explained by Anokhin's model of the activity functional system: unlike activities in a physical environment, where objects of interaction are external to the user, activities in XR environments occur wholly or partially within the user's "internal environment," on a cognitive level. An eventual increase of cognitive work introduced by the characteristics of the learning environment, according to the **Cognitive Load Theory (CLT)** [64–67] can reduce the Learning Performance. In the present study, CLT is therefore employed as a conceptual lens to interpret the findings, while cognitive load itself is not measured directly.

3 Materials and Methods

3.1 Experimental Design

The considered VM application is characterized by two almost identical UIs, based on different XRTs: one is developed for immersive VR technology, while the other is for Mobile AR technology. It proposes a collection of five digital archaeological artefacts: their original copies are kept at the National Archaeological Museum of the Marche in Ancona, Italy. The five artefacts, listed in chronological order of antiquity, were:

- *Statuette (Venus) of Frasassi*, stalactite figurine attributable to a period between 28,000 and 20,000 years ago.
- *Bronze dagger*, datable between 2000 B.C. and 1700 B.C.
- *Kylix*, datable between 470 B.C. and 460 A.D.
- *Pyxis*, datable to about 460 B.C.
- *Augusto capite velato*, datable between 12 B.C. and 14 A.D.

The digital models of the artefacts were obtained from the originals, according to the method proposed in [68], by combining laser scanning, for an accurate acquisition of the artefacts' geometries, and photogrammetry, which allowed the acquisition of photorealistic textures to be applied to the digital models. The two applications shared the same artefacts and, therefore, the same digital reproductions.

Both UIs provide the same functionalities and information. For each artifact, they show a brief textual description that can be toggled using a button (placed on the top right of the artifact). When activated, the description appears

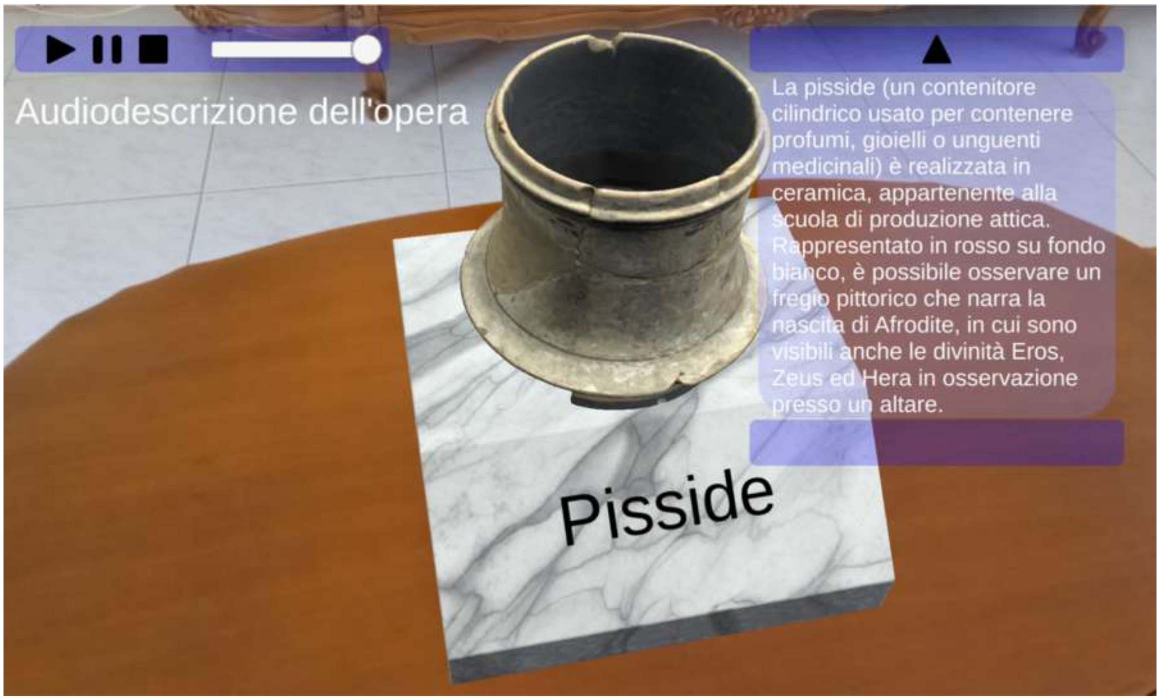

Fig. 1. A screenshot of the AR UI.

with an animation that mimics the unrolling of parchment paper, accompanied by a matching sound effect. Additionally, the same information is available through an audio guide, accessible via media player commands (play, pause, stop, and volume adjustment) placed at the top left of the artifact. The audio guide consists of a voice recording reading the textual description, accompanied by a light musical background.

These design choices were made to ensure a comparable experience between AR and VR settings: the applications provided precisely the same textual descriptions and audio guides, synchronized with matching animations and sound effects to maintain consistent multimedia content across interfaces. Moreover, from a spatial and environmental perspective, the physical context in which participants interacted with the AR application was arranged to mirror the virtual environment used in the VR condition. Specifically, AR participants conducted their experience in a real room furnished and illuminated similarly to the VR environment i.e., minimalist design, soft lighting, and spatial layout closely matching the virtual setup) to ensure that contextual factors did not unduly bias results. Finally, user interface interactions were harmonized: interaction mechanisms, such as content activation buttons and media controls, were kept uniform in layout and functionality across both applications. This ensured that usability differences were minimized, allowing the observed differences in immersion and Learning Performance to be attributed primarily to inherent technological distinctions between AR and VR rather than extraneous design factors.

3.1.1 AR UI. The AR UI (Figure 1), developed using Unity version 2020.3.20f1, was deployed as an Android application. AR functionalities were incorporated using the Vuforia Engine Software Development Kit. Users, with the tablet in their hands and the application active, had the capability to select any target image visible in the environment. Each target image corresponds to a specific artifact. On aligning the tablet's camera with a target image, the application rendered a digital representation of the artifact, positioned on the top of a virtual marble plinth. Concurrently, the application offers a textual description and an audio guide providing relevant

Fig. 2. A screenshot of the VR UI.

information about the artifact. This interactive experience allowed users to explore the artefact in detail, with the added capability of physically moving closer to the target image for an enhanced perspective. Users interact with the AR application's UI using a RealME Pad tablet featuring a 10.4-inch diagonal screen.

3.1.2 VR UI. The VR UI (Figure 2) was developed using Unity version 2020.3.20f1, with the integration of the XR Interaction Toolkit plugin for motion and interactions, and the OculusXR plugin, supporting Meta (formerly Oculus) visor displays and controllers. Users were fully immersed in a virtual room characterized by a parquet floor, black walls and roof, illuminated by a soft, warm light. The minimalist design of the environment was intended to focus the user's attention on the artefacts. In the virtual room, five pedestals were positioned, each bearing an artifact. Each pedestal had a base with a faint blue light-emitting square, making it distinguishable. Users could teleport to an artifact by pointing either controller at the corresponding square and pressing the Grab button. A tunneling transition was employed during teleportation to mitigate potential cybersickness. Upon arrival near a pedestal, users could walk freely within a 1-metre radius around it. If users moved beyond this boundary, the application would halt, and the headset would switch to see-through mode, showing the real world to prevent collisions with real-world obstacles.

Unlike the AR-based one, this UI remains fixed in space within the virtual artefacts, and it is activated only when the user approaches an artifact, keeping the other four instances invisible. This design choice aimed to reduce cybersickness, as evidence suggests that a constantly visible, user-following UI in VR can induce nausea. Interaction with the UI was achieved by pointing at it with either controller and pressing the Trigger button. The UI's two halves were slightly angled toward the user to enhance immersion.

3.2 Data Collection

The testing sessions were conducted following a quasi-experimental approach, during a public outreach event where several archaeological artefacts belonging to the National Archaeological Museum of Ancona, Italy, were

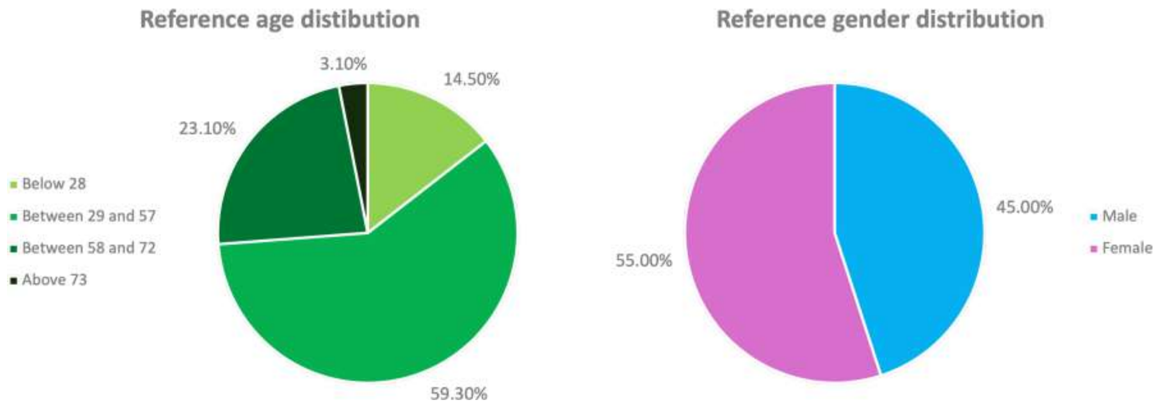

Fig. 3. Demographic distributions.

virtually displayed to the public. This setting facilitated the recruitment of a diverse sample group, encompassing a wide range of visitors. We operated a booth where we displayed AR and VR technologies, attracting attendees who exhibited interest or posed questions. People aged at least 18 were recruited on a voluntary basis from these engaged individuals. After being recruited, participants were taken to an adjacent room furnished similarly to the one depicted in the VR version of the app. This allowed AR app users to participate in the experience in a similar setting to VR app users. They were allowed to explore the applications at their own pace, free from time restrictions. The only request made to them was to acquire as much information as possible on all five artefacts. Immediately following the completion of the test, participants were presented with an electronic questionnaire.

This enabled us to collect an extensive pool of volunteer participants (n = 261). This pool was diverse in terms of demographics and geographic background, reflecting a broad spectrum of potential visitors to medium-sized Italian archaeological museums. From this pool, two samples were carefully selected to mirror the demographic segmentation typically observed in these museums. Specifically, we chose participants to match the age and gender distribution commonly found among museum visitors. This step ensured that both samples were representative of the actual visitor demographics. In addition to demographic factors, geographic characteristics were also considered. Participants were selected to reflect the usual geographic distribution of visitors to medium-sized Italian archaeological museums, which are predominantly regional with a smaller proportion of national visitors. This criterion was crucial for maintaining ecological validity and ensuring that the sample accurately represented the museum's visitor profile. Finally, we ensured that users with professional profiles in the fields of history, art history, and archaeology were not included in the sample to avoid introducing a knowledge bias. Additionally, we administered a brief preliminary questionnaire to participants to assess their specific knowledge regarding the artefacts displayed in the VM, similar to [69]. This screening tool enabled us to include in the sample only those visitors who demonstrated no prior specific knowledge about the artefacts. Finally, to facilitate a balanced comparison, equal numbers of participants who had tested the VR and AR experiences were included in each sample. This parity was essential to ensure that any observed differences in user experiences could be attributed to the VR and AR modalities rather than disparities in participant numbers. The distributions of age and gender within the AR and VR samples, as well as the reference demographic distribution, are presented in Figure 3. Each group (AR and VR) consisted of 88 participants, for a total of 176 users.

3.3 Measures

The questionnaire has been organized into three different sections.

3.3.1 Section A "Personal Information." This section gathered basic demographic and geographic information, such as age, gender, and hometown. Additionally, it inquired about participants' self-reported familiarity with XRTs, asking to rate their agreement with the following two statements on a five-point Likert scale (i.e., "I am familiar with augmented/virtual reality technologies"). The Likert scale ranged from 1 (Strongly Disagree) to 5 (Strongly Agree). Additionally, a question was related to the user's knowledge background (i.e., "Do you have specific training or are you passionate about history, art history or archaeology?") to avoid introducing a knowledge bias into the sample.

3.3.2 Section B "User Immersion." User Immersion was assessed through the ARI questionnaire [44], which consists of 21 items. For the VR version, we changed the word "AR" with the word "VR."

3.3.3 Section C "Learning Performance." This final section was designed to evaluate the acquisition of specific knowledge related to the characteristics of the artefacts featured in the VM application. It comprises a total of 15 multiple-choice questions, with each artifact being assessed through three questions, each having a single correct answer. We opted for a test format over self-reported measures because the latter tend to reflect users' perceptions and attitudes rather than actual Learning Performance [70]. To ensure the integrity of the results, the order of the answers was randomized, minimizing the likelihood of communication among participants affecting the performance. The test was developed in collaboration with an academic expert in Ancient History. The questions aim to investigate the understanding of aspects related to both the aesthetic and functional characteristics of the artefacts (e.g., "What is the scene depicted on the Pyxis?"; "What was the Kylix used for?"), as well as the historical and anecdotal information provided in the descriptive texts (e.g., "Why is Augustus depicted with a veiled head?"). One point was awarded for each correct answer, while no points were awarded for incorrect or unanswered questions. To engage users by offering immediate feedback on their performance, thus encouraging a more interactive and rewarding experience, the results have been provided at the end of the questionnaire.

3.4 Statistical Methods

Statistical analysis was performed with IBM SPSS Statistics v20. Given the non-normal distributions of all the collected measures (both Kolmogorov–Smirnov and Shapiro–Wilk tests $p < .05$) we opted for non-parametric tests. We performed Mann–Whitney U test to assess the differences between groups regarding the factors Age, Familiarity with XR technologies, while we used a Chi-square test to assess the differences regarding Gender.

To determine the differences between groups (AR vs. VR) regarding User Immersion (and its scales) and Learning Performance, we performed Mann–Whitney U tests. To assess the effect within groups of the factors Age, Gender, and Familiarity, we performed the Kruskal–Wallis test.

Finally, Spearman's correlation analysis (performed using R software and the Hmisc package) was conducted to evaluate the eventual relationships between the assessed scale and Learning Performance.

4 Results and Discussion

The results indicate that there are no statistically significant differences between the groups in terms of age (AR: $M = 46.125$, $SD = 15.543$, $Mdn = 45.00$; VR: $M = 47.056$, $SD = 16.646$, $Mdn = 44.50$), gender (AR: 47 females and 41 males; VR: 48 females and 40 males), and familiarity with AR or VR technologies. Participants from both groups reported low familiarity with AR ($M = 1.73$, $SD = 1.396$, $Mdn = 2.00$) and VR ($M = 2.09$, $SD = 1.23$, $Mdn = 2.00$). Therefore, we can assume that the participants were evenly distributed across the groups with respect to these characteristics.

The Mann–Whitney U test results showed that the effect of the Technology factor on Learning Performance was statistically significant ($U = 3{,}088.00$, $p = 0.017$). As depicted in Figure 4, AR users achieved higher average Learning Performance ($M = 7.227$, $SD = 1.295$, $Mdn = 8.00$) compared to VR users ($M = 5.590$, $SD = 0.286$, $Mdn = 6.00$). Regarding User Immersion, the effect of the Technology factor was not statistically significant. While Technology

Fig. 4. Learning Performance scores and Total Immersion values, by technology.

did not significantly affect Engagement and Engrossment, the test revealed a statistically significant effect of Technology on Total Immersion (U = 4,768.00, $p = 0.008$). VR users reported higher Total Immersion (M = 5.135, SD = 1.002, Mdn = 4.835) than AR users (M = 4.694, SD = 1.135, Mdn = 4.670).

Regarding the subscales, Mann–Whitney U tests highlighted statistically significant effects of the Technology factor on Focus of Attention (U = 4,688.00, $p = 0.015$), Presence (U = 4,744.00, $p = 0.010$), and Flow (U = 4,672.00, $p = 0.017$). Specifically, as shown in Figure 5, VR users experienced higher Focus of Attention (VR: M = 5.241, SD = 1.026, Mdn = 5.500; AR: M = 4.908, SD = 1.167, Mdn = 5.165), higher Presence (VR: M = 5.239, SD = 1.242, Mdn = 5.375; AR: M = 4.705, SD = 1.332, Mdn = 4.875), and higher Flow (VR: M = 5.030, SD = 1.162, Mdn = 5.165; AR: M = 4.682, SD = 1.123, Mdn = 4.500). On the other hand, no statistically significant differences were found regarding the levels of Interest, Usability, and Emotional Attachment reported by participants.

In terms of Engagement and its subscales (i.e., Usability and Interest), we found no statistically significant differences. This result aligns with our expectations, as both interfaces deliver the same content through a UI that provides the same functionality and information and has an almost identical layout of commands. Consequently, the characteristics of the two types of interfaces did not lead to substantial differences in terms of the ability to elicit Interest or the level of perceived Usability.

Although both interfaces were found to be equally usable, it is conceivable that VR causes a shift of attention in the user due to a "wow effect," which prevents the user from fully concentrating on the content. This can be confirmed by the fact that the Focus of Attention value reported by VR users was significantly higher than that reported by AR users.

As for the non-significance of the difference in Emotional Attachment values reported by the participants, this could be explained, as in the case of Interest, by the fact that the two interfaces and the content they present are not able to arouse significant levels of curiosity, excitement, and escapism in users.

The higher levels of Presence reported by VR users compared to AR users are consistent with literature reports that high levels of Presence are more difficult to achieve in AR than in VR [46, 47]. Likewise, the state of Flow,

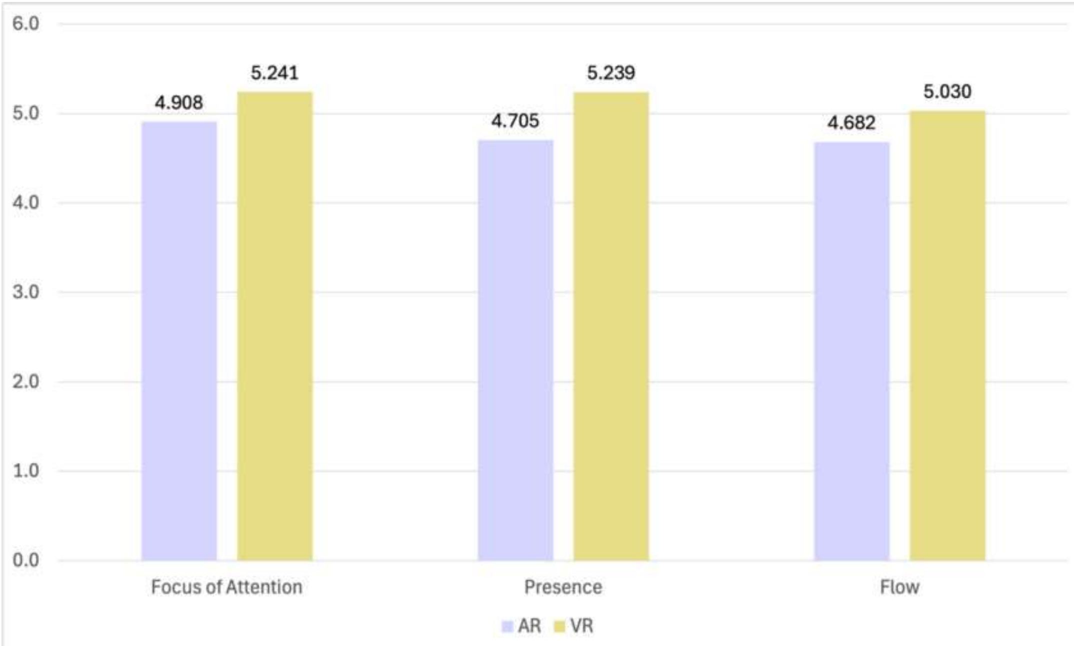

Fig. 5. Focus of Attention, Presence, and Flow values, by technology.

and consequently Total Immersion, can be extremely transient in AR, as various external factors can contribute to distracting the user from the experience (e.g., object tracking errors, hardware challenges, the screen being too bright in outdoor activities, or weather adversities) [71–73].

Considering these results, the higher level of Learning Performance achieved by AR users compared to VR users could be justified by several reasons. On the one hand, all users started from the same low level of familiarity. AR users, however, found themselves interacting with a device (the tablet) with which they were probably more familiar than VR users were with the headset. Consequently, VR users may have experienced a higher cognitive load due to having to learn content while simultaneously learning how to interact with a new technology. As confirmed in literature (e.g., [60]), participants' unfamiliarity with new equipment may have an impact on their performance, as individuals need time to adapt to new technological systems.

In fact, CLT [64–67] suggests that the amount of information that can be simultaneously stored and processed by an individual (**Cognitive Load (CL)**) is limited [74]. This represents a critical factor in learning [75], as if the working memory capacities of learners are exceeded, learning is hindered due to excessive cognitive processing demands [76]. As it is known, three types of CL can occur during a learning activity: intrinsic, extraneous, and germane [65–67]. When user-instructional material interaction is mediated by an unfamiliar interaction technology (i.e., VR technologies), an excessive extraneous CL may result, as the user is simultaneously performing a double learning task: understanding how to interact with the new device and interface, and processing the information conveyed by the instructional material. Moreover, another possible factor negatively influencing Learning Performance could have been the above-mentioned "wow effect," due to which VR users may have paid more attention to the environment and experience in general rather than the content presented to them.

It is important to note, however, that CL was not directly measured in this study. Therefore, our interpretation should be considered a theoretically plausible explanation, grounded in CLT and consistent with findings from

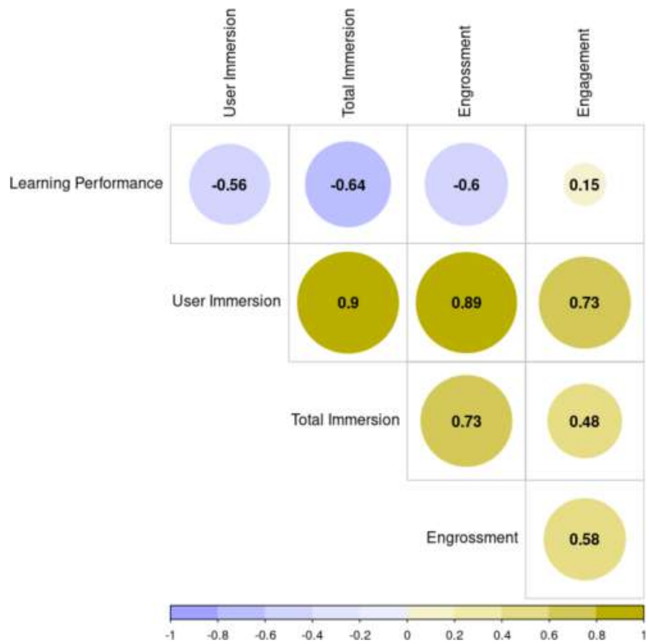

Fig. 6. Spearman's rho correlation values between Learning Performance, User Immersion, Total Immersion, Engagement, and Engrossment.

prior XR learning research. Future work incorporating validated subjective (e.g., NASA-TLX) or physiological measures of CL would be necessary to empirically substantiate this account.

Moreover, exposure time to the applications was neither fixed nor recorded: participants were allowed to explore the experience at their own pace, as they would during a real museum visit. While this choice enhances ecological validity, it also introduces a potential confounding variable, insofar as differences in time-on-task between the AR and VR groups may have contributed to the observed learning outcomes. Future studies should therefore control or systematically log exposure duration, and possibly combine these data with measures of comfort, fatigue, and adaptation to the devices, in order to disentangle the specific contribution of the technology from that of the time spent interacting with it.

The results of Spearman's correlation analysis, conducted on the whole pool of data regardless of the Technology factor, are reported in Figure 6. They indicate a significant and moderate negative relationship between Learning Performance and User Immersion ($rs(174) = -0.564$, $p = 0.046$). Additionally, there are significant negative relationships between Learning Performance and Total Immersion, $rs(174) = -0.638$, $p = 0.041$, and between Learning Performance and Engrossment, $rs(174) = -0.598$, $p = 0.044$, while there is a significant and weak positive relationship between Learning Performance and Engagement, $rs(174) = -0.153$, $p = 0.043$.

These findings suggest that higher levels of User Immersion are associated with lower Learning Performance. This pattern is compatible with the hypothesis that factors such as Total Immersion and Engrossment may detract from the learning task, possibly by increasing cognitive load; however, this mechanism remains speculative in the absence of direct cognitive load measures. Conversely, the Engagement factor plays a positive role in supporting Learning Performance. This result confirms what is well known in the literature: the usability of the interface and its ability to stimulate user interest directly impact the effectiveness of the learning mediator in supporting the learning task. However, although we stratified the samples to mirror the typical demographics of that museum's adult visitors and excluded participants with specialized training in history, art history, or archaeology, the results may not straightforwardly extend to other museum types (e.g., art galleries, science centers, and highly gamified installations) or to other visitor groups such as children, school classes, older adults, or people with disabilities. Future studies are needed to explore the interaction between User Immersion and Learning Performance in other settings and with different user's groups.

Given our findings, XR applications in museum contexts should be designed to optimize engagement and usability rather than to maximize immersion at all costs. When the primary goal is factual knowledge acquisition, our findings suggest that AR or other moderately immersive solutions that preserve a strong coupling with the physical environment and rely on familiar interaction modalities may be preferable, provided that they offer clear information structure and simple, consistent interaction vocabularies. Fully immersive VR, by contrast, appears better suited to objectives such as affective engagement, attitudinal change, or the creation of memorable experiential "highlights," and should be positioned as a complement to, rather than a replacement for, more instructional experiences.

5 Conclusions

This article presents a quasi-experimental study involving visitors of the National Archaeological Museum of Ancona in Italy, aimed at comparing the evaluation of two UIs of a VM system, based respectively on VR and AR technologies, in terms of User Immersion and resulting Learning Performance. The main contribution of this article is a comprehensive evaluation of the effect of User Immersion on Learning Performance of users of VMs. The comparative analysis results highlighted that the Technology factor leads to statistically significant differences in Learning Performance (with AR users reporting higher scores) and in Total Immersion, Focus of Attention, Presence, and Flow (with VR users reporting higher scores). No statistically significant differences due to the Technology factor were observed in the other scales analyzed. The correlation analysis results, on the other hand, indicated a moderate negative correlation between User Immersion, Total Immersion, and Engrossment with Learning Performance, as well as a weak positive correlation between Engagement and Learning Performance. None of the other scales analyzed showed a correlation with Learning Performance.

Taken together with the correlation analyses, these findings may suggest that higher levels of Total Immersion and Engrossment are associated with lower Learning Performance and could be linked to increased cognitive demands for the user. Because cognitive load was not measured directly in this study, this explanation should be regarded as tentative and theory-driven. Conversely, as confirmed by existing literature, an interface that offers good Usability and the ability to stimulate Interest (and thereby Engagement) in the users directly enhances the effectiveness of the learning mediator in supporting the learning task.

The results of the present study suggest that Engrossment and Total Immersion may be negatively associated with Learning Performance in a VM context. A plausible explanation is that these factors increase cognitive load and thus act as antecedents of reduced performance. However, we did not collect any direct indicators of cognitive load, so this mechanism remains hypothetical.

Conversely, the Engagement factor—through the Interest and Usability subscales—appears to positively influence Learning Performance. Specifically, regarding the Interest subscale, this study did not explore whether and how differences in users' learning styles and personal interests impact Learning Performance.

Additionally, the effect of different technologies on the retention of knowledge acquired during the VM visit was not examined. A longitudinal study is necessary to explore this aspect. Lastly, the exposure time to the application was not controlled, with users allowed to interact with it for as long as they deemed necessary to learn the presented notions. This time factor might have influenced Learning Performance.

5.1 Future Works

In order to explore the likely cognitive workload-mediated negative effect of Engrossment and Total Immersion on Learning Performance in a VM context, future studies will integrate standardized cognitive load measures (e.g., subjective workload questionnaires or physiological indicators) to test whether differences in learning outcomes between AR and VR are indeed mediated by cognitive overload.

Also, future research will delve into the topic of how the differences in users' learning style impact Learning Performances, while also considering different museum types (e.g., art galleries, science centers, and highly gamified installations) and different visitor groups (e.g., children, older adults, and people with disabilities).

Finally, future research will also explore the use of AR specifically in augmentation rather than substitution of real artefacts, examining how different degrees of visual and contextual augmentation might impact learning outcomes, especially in comparison to fully immersive VR experiences. Additionally, since exposure duration was intentionally uncontrolled in this study to replicate natural museum visitation conditions, future works will explicitly address this limitation by controlling or systematically measuring exposure times, alongside user comfort levels and adaptation to AR and VR technologies, to better isolate their effects on User Immersion and Learning Performance. Moreover, the present analysis was limited to User Immersion and Learning Performance, neglecting other potentially influential dimensions such as Motivation, Confidence, Intention to Use, Overall User Experience, and Technology acceptability. Future research could incorporate standardized questionnaires, such as the Technology Acceptance Model or the User Experience Questionnaire, to provide a more comprehensive understanding of the factors influencing user interaction with AR and VR applications in museum settings. Future studies could then benefit from incorporating evaluations from museum curators, educators, or technology experts, thus enriching the findings with professional insights and practical recommendations for museum implementation.

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