7 (2023) 100057

Contents lists available at ScienceDirect

Data and Information Management

journal homepage: www.journals.elsevier.com/data-and-information-management

An empirical study on user experience evaluation of VR interface in digital museums

Xi Pei [a], Shiting Fu [a,*], Tingting Jiang [a,b]

[a] School of Imformation Management, Wuhan University, Wuhan, Hubei, China
[b] Center for Studies of Information Resources, Wuhan University, Wuhan, Hubei, China

ARTICLE INFO

Keywords:
Digital museums
Virtual reality
User experience

ABSTRACT

Virtual reality (VR) has been increasingly introduced to digital museums to enable more immersive experiences. However, there is a lack of comprehensive evaluation for user experience in VR-based digital museums. A comprehensive framework for evaluating user experience of VR interfaces in digital museums was created. Based on this framework, the study conducted an experiment to investigate learning effectiveness in VR-based digital museums and compared user experience on desktop and mobile devices. A total of 45 participants were recruited. They were asked to visit a digital museum on either a desktop or a mobile device. After they completed their visit, they took a recognition test and a recall test to measure their effectiveness of learning. Their user experience was evaluated using a new scale, followed by an open-ended interview to collect their opinions and feedback. It was found that introducing VR to the digital museum helped increase users' effectiveness of learning. Significant differences existed between the desktop and mobile VR interfaces in user experience. It means that previous research findings cannot be directly applied to the user experience of digital museums on mobile. These empirical evidences also suggest that the established framework is effective for evaluating the user experience in VR-based digital museums.

1. Introduction

Digital Museum is a museum system to present traditional museums on the internet in three dimensions with computer network technology, virtual reality technology (VR), and other digital technologies (Wang, Dong, Wu, & Wu, 2014). Digital museums broaden access to traditional museums, enabling people to visit online exhibitions without the constraints of time and space (Hu, Han, Wang, Peng, & Yang, 2023). Users can visit it through various devices such as desktop devices and mobile phones (Wu, Jiang, Liang, & Ni, 2022). To achieve the above purpose and provide better interactive and immersive experiences, virtual reality (VR) and augmented reality (AR) technologies have been widely used in digital museums (Guo, Fan, Lehto, Day, & Research, 2021).

According to International Council of Museums, museum is a non-profit, permanent institution in the service of society and its development, open to the public, which acquires, conserves, researches, communicates and exhibits the tangible and intangible heritage of humanity and its environment, for the purposes of education, study and enjoyment (Agostino & Arnaboldi, 2021). It emphasizes the importance of museums in providing educational and recreational services to the public. Museum Hack conducted a poll on Twitter. The results showed that audiences value museums for their entertainment value and the museum professionals who run them focus more on educational value (Hack, 2016). The educational value and entertainment value correspond precisely to the two dimensions of Culture User Experience (CUX): pragmatism and hedonism. CUX is defined as "The unique produced knowledge and experience from different cultural identities" (Konstantakis, Michalakis, Aliprantis, Kalatha, & Caridakis, 2017). It goes beyond the usability of a cultural product or system, incorporating both pragmatic (function and features) and hedonic (user expectation, motivation, and feelings) factors (Konstantakis, Caridakis, & Heritage, 2020). Given the dual role of digital museums, this study focused on the two dimensions of CUX: pragmatism (knowledge dissemination) and hedonism (providing a better experience for users).

In the current research on cultural user experience in digital museums, there are still some research gaps. First, numerous studies have focused on evaluating the user experience of digital museums. However, previous studies have selected different dimensions, each with its own focus. The lack of a comprehensive and general framework leads to two problems in theory and practice. From a theoretical perspective,

* Corresponding author.
E-mail addresses: 2018301040247@whu.edu.cn (X. Pei), fushiting@whu.edu.cn (S. Fu), tij@whu.edu.cn (T. Jiang).

https://doi.org/10.1016/j.dim.2023.100057
Received 6 April 2023; Received in revised form 19 October 2023; Accepted 8 November 2023
Available online 13 November 2023

researchers encounter difficulties when comparing and integrating the results from various studies. It hinders the construction and development of comprehensive theoretical modes. From a practical perspective, it cannot provide detailed theoretical guidance for the evaluation and improvement of user experience in VR-based digital museums.

Our study aims to create a framework for evaluating digital museum VR interfaces. The framework is designed to offer a thorough evaluation of the educational and entertainment dimensions of the digital museum experience, encompassing both its pragmatic and hedonistic aspects. It is intended to be a practical tool for application in the production and design of digital museums.

RQ1: What are the constituent elements of the user experience evaluation framework for digital museums?

CUX focuses on two dimensions, pragmatism and hedonism. Previous studies have suffered from the following research gap in terms of pragmatism. Researchers have paid attention to learning experiences in museums. While most of them use questionnaires and interviews to gather data (Hsu, Liang, Chiou, Tseng, & Applications, 2018; Poce, Amenduni, De Medio, Valente, & Re, 2019). It is not always reliable since they may be confounded by a broad range of factors, like self-presentation (Stroud, 2008), preference falsification (Kuran, 1997) and subjective interpretation by researchers (Heyman, 1979).

Hence, we employ tests to measure the effectiveness of learning in digital museums. Recall tests and recognition tests are typically utilized to gauge the extent of learning mastery (Butler & Roediger, 2007; Carpenter & Delosh, 2006; Zhang, 2015). These methods are more precise and can reduce subjectivity. Furthermore, tests are quantitative methods that can effectively reduce researcher-induced subjective interpretations that may arise from questionnaires and interviews (Heyman, 1979). The combination of these two assessments allows for a more precise evaluation of users' study during their visits in digital museums (Zhang, 2005).

RQ2: Does VR technology promote the effectiveness of learning in digital museums?

In terms of hedonism, despite the surge in usage, there is little research on user experience of digital museums on mobile. Desktop devices and mobile devices are two important ways of presenting digital museums. In academic research, scholars predominantly use desktop platforms. However, in the real world, users predominantly utilize mobile platforms. Therefore, it is imperative to compare the user experiences between digital museums on desktop and digital museums on mobile, aiming to investigate the extent to which prior conclusions drawn regarding digital museums on desktop remain applicable to the emerging realm of digital museums on mobile.

RQ3: Does user experience of VR interfaces in digital museums differ on desktop and mobile devices?

This study presents an experiment to study the UX of the digital museum VR interfaces combining the characteristics of VR. Our purpose is to create a framework for evaluating the user experience of digital museum VR interfaces and to promote the development of digital museums using VR.

2. Literature review

2.1. The situation of applying virtual reality in digital museums

The application of VR technology in digital museums is a popular trend nowadays. VR technology offers innovative solutions to recreate historical scenes, engages users through immersive narratives, and provides interactive gaming experiences. Several studies have harnessed VR technology to augment digital museum experiences in various ways.

Many studies applied VR technology to recreate scenes. Researchers utilized 3D modelling to recreate the physical museum's panoramic view (Bozzelli et al., 2019; Louvre Museum, 2021). These initiatives demonstrate the potential for VR to bring museums to users, eliminating the need for physical attendance. Through the recreating of scenes, some projects showcase the importance of VR in safeguarding historical sites and artifacts (Loizides, El Kater, Terlikas, Lanitis, & Michael, 2014; Ch'Ng, Li, Cai, & Leow, 2020).

VR technology has been leveraged to provide interactive digital storytelling in digital museums (Škola et al., 2020; Garzotto, Matarazzo, Messina, Gelsomini, & Riva, 2018; Rizvić et al., 2021). On this basis, some studies have integrated gaming elements into digital museums using VR (Anastasovitis & Roumeliotis, 2023; Puig et al., 2020). For instance, Puig et al. (2020) reconstructed an archaeological museum and added a game component to enhance the learning experience. These approaches demonstrate the capacity of VR to make museum content more engaging and accessible.

To ensure that adding VR technology in digital museums achieves positive effects mentioned above, most studies focused on the user experience of digital museums. Multiple studies have explored various aspects of user experience. Findings suggest that VR enhances perceived presence, immersion, realism and overall satisfaction (Anastasovitis et al., 2023; Škola et al., 2020). Arayaphan, Intawong, and Puritat (2022) evaluated content, learning, usability, and user experience of a VR-based museum and indicated that VR technology significantly improved the overall user experience of digital museums. Additionally, it was noted that VR can facilitate museum learning (Arayaphan et al., 2022; Ch'Ng et al., 2020). However, most of them relied on the self-report approach by directly asking users about their feelings, taking the form of questionnaires (Arayaphan et al., 2022; Ch'Ng et al., 2020) and interviews (Loizides et al., 2014). It results in potential limitations such as social desirability bias (Davis, Thake, & Vilhena, 2010), recall bias (Coughlin, 1990), and so on.

Furthermore, previous evaluations of digital museums have often suffered from one-sided issues. For the selection of research subject, the studies mentioned above were concerned with digital museums on desktops, which rarely mentioned digital museums on mobile. For the selection of evaluation indicators. Previous studies have typically failed to consider the multifaceted functions of digital museums. Only one aspect of the indicators was selected for evaluation.

2.2. Cultural user experience enabled by virtual reality

CUX is the theory that effectively guides the evaluation of user experience in digital museums. CUX includes both pragmatic (function and features) and hedonic (user expectation, motivation, and feelings) factors (Konstantakis & Caridakis, 2020). Research articles on CUX of virtual reality technology generally consist of the following components: hedonism, and pragmatism.

In the aspect of hedonic, research articles generally focused on users' expectations and feelings. Authors generally placed an emphasis on the feeling of immersion, presence, and enjoyment after using VR technology in cultural sites such as museums and galleries (Ch'Ng, Li, Cai, & Leow, 2020; Mccaffery, Miller, Vermehren, & Fabola, 2016; Pantile, Frasca, Mazzeo, Ventrella, & Verreschi, 2017; Škola et al., 2020; Verhulst, Woods, Whittaker, Bennett, & Dalton, 2021). They also evaluated user engagement and satisfaction (Kang & Yang, 2020; Loizides et al., 2014; Mccaffery et al., 2016; Škola et al., 2020; Verhulst et al., 2021). Some studies focused on the user's emotion (Bozzelli, Raia, Ricciardi, Nino, & Palombini, 2019), content evaluation of the product (Škola et al., 2020), and the state of flow (Škola et al., 2020).

Some studies include the pragmatic factors in CUX(Hammady, Ma, Strathearn, & Heritage, 2020; Loizides et al., 2014). Some have taken into account usability and learning. Some have added learning experiences to the UX (Ch'Ng et al., 2020; Higgett, Chen, & Tatham, 2015;

Kang & Yang, 2020; Mccaffery et al., 2016).

It was found that CUX of virtual reality technology includes pragmatic and hedonic factors. The pragmatic factors usually include usability and learning through the review of previous studies. The hedonic factors usually include expectation, attitude, intention and enjoyment, immersion, presence, and engagement. It can be seen that there are many evaluation dimensions of CUX. However, most researchers did not give a rationale for using certain dimensions to evaluate (Ch'Ng et al., 2020; Škola et al., 2020). Most of the assessments were one-sided. Few studies have comprehensively evaluated digital museums from a CUX perspective. A majority of studies excessively relied on the self-report approach by directly asking users about their learning outcomes (Ch'Ng et al., 2020; Li & Chang, 2017), which may be affected by desirability bias (Davis et al., 2010) and recall bias (Coughlin, 1990).

2.3. Digital museum virtual reality interface user experience evaluation

UX is a consequence of a user's internal state (predispositions, expectations, needs, motivation, mood, etc.), the characteristics of the designed system (e.g. complexity, purpose, usability, functionality, etc.) and the context (or the environment) within which the interaction occurs (e.g. organizational/social setting, meaningfulness of the activity, voluntariness of use, etc.) (Hassenzahl and Tractinsky, 2006). Hence, the UX of the digital museum VR interfaces is also the result of the above three factors.

In terms of the user's internal state, it is crucial to consider factors such as expectations and mood. In accordance with the literature review in Section 2.2, experiential considerations related to VR technology should also be a focal point of our investigation. Hence, it is imperative to focus on dimensions such as Enjoyment, Immersion, Presence, and Expectation. This corresponds to hedonic in CUX.

In terms of the characteristics of the designed system, it is essential to focus on issues related to the system's usability and functionality. Therefore, the selection of usability and learnability as sub-dimensions for the framework is paramount.

In terms of the context (or the environment) within which the interaction occurs, education corresponds to the "meaningfulness of the activity" in digital museums. This also aligns with pragmatic in CUX. "Voluntariness of use" should be included in the framework. Therefore, the third part of the framework contains Learning, Attitude and Intention.

Combining Hassenzahl's model, CUX, and relevant previous research on digital museums in the literature, a framework was created for evaluating the cultural user experience of VR-based digital museum (see Table 1).

3. Methods

3.1. Participants

Participants were recruited from a university in China. Researchers posted a recruitment advertisement on social media that clarified the purpose and requirements of this experiment. It requires that participants were interested in our study and could meet the schedule of our experiment. Participants were required to complete a questionnaire to report their age, gender, and their convenient time for participation.

Ultimately, this study attracted a total of 60 enrollments. Chosen after screening, a total of 45 students, aged between 18 and 29, participated in the experiment. They are undergraduate or postgraduate students, including 14 males and 31 females. Each participant received 20 RMB for their time.

Previous surveys have shown that youth is the main user group of VR products (Zeng, 2022). Therefore, we chose undergraduate or postgraduate students as experimental participants. A large number of previous studies have shown the generalizability of using college students as research subjects (Berkowitz & Donnerstein, 1982; Kardes, 1996; Lucas, 2003; Wiecko, 2010). Using student samples in this study does not affect the validity of results.

The participants were equally divided into three groups that would browse a digital museum on different devices. Data for 3 participants were disregarded due to short answer time or invalid answers (the options checked in the whole questionnaire are the same or regular). Participants were allocated to conditions as follows: desktop group (N = 15, 10 female), mobile group (N = 14, 10 female), and no-VR group (N = 13, 9 female). Demographic characteristics of the participants in the study are shown in Table 2.

3.2. Apparatus and stimuli

Before conducting the experiment, we conducted a survey of VR-based digital museums both domestically and internationally. Currently, the majority of these digital museums primarily employ 360-degree panoramic technology. Their modes of presentation and interaction methods exhibit a high degree of uniformity. Among them, "The Panorama Palace Museum" stands out due to its advanced functionality and presentation style.

"The Panorama Palace Museum" is an application using VR technology to display the scene of the Palace Museum. It enjoys widespread popularity among domestic users. Users can visit the Palace Museum online with it. Participants in the desktop group browsed it on the website (https://pano.dpm.org.cn/gugong_pano/index.html) (see Fig. 1). The mobile group browsed it on the mini app (see Fig. 2). The no-VR group used printed paper materials. The three groups watched the same content.

3.3. Task and procedures

All participants were informed about the purpose of the research. They were assigned to different groups (desktop group, mobile group, or no-VR group) and all of them completed a consent form.

Table 1
A framework for evaluating UX of VR interfaces in digital museums.

Evaluation dimensions	Sub-dimensions	References
Users' perceptions	Enjoyment	Hammady, Ma, and Strathearn (2020)
	Immersion	McCaffery, Miller, Vermehren, and Fabola (2015)
	Presence	Verhulst et al. (2021)
	Expectation	Ch'Ng et al. (2020)
System usability	Usability	McCaffery et al. (2015)
	Learnability	McCaffery et al. (2015)
Effectiveness of learning, attitude, and intention	Learning	McCaffery et al. (2015)
	Attitude	Hong et al. (2013)
	Intention	Hammady et al. (2020)

Table 2
Distributions of socio-demographic characteristics of different groups.

Demographics		desktop group		mobile group		no-VR group	
		n	%	n	%	n	%
Gender	Female	10	66.7	10	71.4	9	69.2
	Male	5	33.3	4	28.6	4	30.8
Age	<18 years old	0	0	0	0	0	0
	18–25 years old	14	93.3	14	100	12	92.3
	>25 years old	1	6.7	0	0	1	7.7
Education level	Undergraduate students	12	80.0	12	85.7	11	84.6
	Postgraduate students	3	20.0	2	14.3	2	15.4

Fig. 1. "The Panorama Palace Museum" on desktop.

3.3.1. Pretests

First, participants needed to complete the pre-tests. Demographics and participants' familiarity with the Palace Museum and VR technology were collected in the pretest. The questions included "Have you been exposed to VR technology before.", "Have you visited the Palace Museum before." and "Have you paid attention to the knowledge related to the Palace Museum before." The 5-point Likert scale questionnaire was applied.

Researchers wrote some questions to test the participants' knowledge of the Palace Museum (See Appendix A). The purpose of the test was to exclude the impact of prior knowledge on this study. Ensuring that there was no significant difference in the participants' knowledge of the Palace Museum.

3.3.2. Browsing task

Participants were asked to browse according to the researchers' instructions and to browse freely. When browsing according to the instructions, participants first read cards and then browsed the Hall of Supreme Harmony, the Hall of Preserving Harmony, the Palace of Heavenly Purity, the Palace of Earthly Tranquility, the Palace of Fasting, and the Hall of Sincerity and Solemnity. This route is simplified according to the popular tourist route of the Palace Museum recommended on the Internet. Then participants used the system freely. The time is recorded accurately.

3.3.3. Posttests

After the browsing task, participants were required to complete a recognition test (refer to Appendix B) and a recall test (refer to Appendix C), along with a questionnaire evaluating their CUX (refer to Appendix D). Additionally, an open-ended interview was conducted with each participant.

The recall test and recognition test were used to measure the effectiveness of learning after visiting digital museums. Participants with relatively high scores indicated gaining more knowledge in digital museums. The questions for the recall test and recognition test were based on the content of "The Panorama Palace Museum". The recall test consisted of 6 fill-in-the-blank questions, with 2 points for each blank. The recognition test consists of 6 multiple-choice questions and 3 true-false questions, each with a score of 2 points.

The experiment also included a questionnaire and an individual interview. The questionnaire was used to collect user experience information. Participants were asked about their opinion toward the digital museum during the interview (i.e., advantages and disadvantages).

The whole procedure can be seen in Fig. 3.

3.4. Measures

According to the framework described in chapter 2.3, this study measured user experience in three aspects: users' perceptions, system usability, and effectiveness of learning, attitude, and intention. The items are listed in Appendix D.

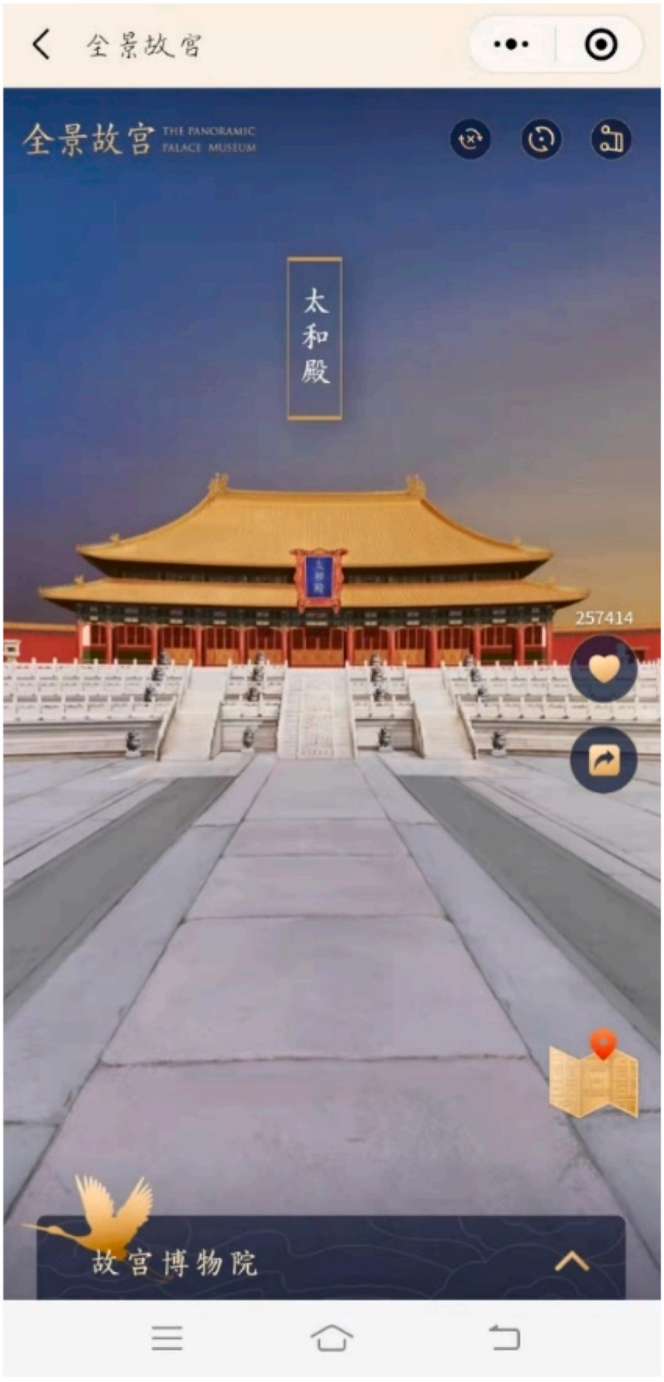

Fig. 2. "The Panorama Palace Museum" on mobile devices.

3.4.1. Users' perceptions

Enjoyment was evaluated with three items (Hall, 2009). A 5-point scale (1 = strongly disagree, 5 = strongly agree) was used to record the responses.

Immersion was evaluated with four items (Schaufeli, Salanova, González-Romá, & Bakker, 2002). Responses were recorded on a 5-point Likert-type scale (1 = strongly disagree, 5 = strongly agree).

Presence was assessed with four items (Schubert, Friedmann, & Regenbrecht, 2001). Responses were recorded on a 5-point Likert-type scale (1 = strongly disagree, 5 = strongly agree).

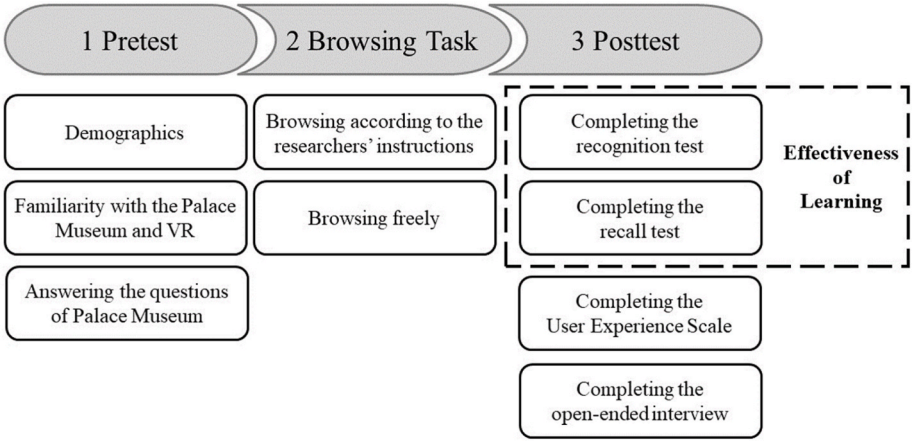

Fig. 3. Experiment procedures.

Expectation was evaluated via three items, adapted from the scale of Bhattacherjee (2001). A 5-point scale (1 = strongly disagree, 5 = strongly agree) was used to record the responses.

3.4.2. System usability

The System Usability Scale (SUS) (Grier, Bangor, Kortum, & Peres, 2013) was used to measure the usability and learnability of the digital museum. SUS includes 10 items and uses a 5-point scale (1 = strongly disagree, 5 = strongly agree) to record. The subscale composed of the fourth and tenth items in the SUS scale is to evaluate "learnability". The subscale composed of the other 8 items is to evaluate "usability".

3.4.3. Effectiveness of learning, attitude, and intention

The effectiveness of learning was evaluated with the recognition test and recall test. The recognition test and recall test were compiled according to the content watched by the participants. They were related to the knowledge of the Palace Museum displayed in the digital museum. The recognition test was all blank filling tests. The recall test includes multiple-choice questions and judgment questions.

Attitude was evaluated with four items (Moon, Kim, & management, 2001). Responses were recorded on a 5-point Likert-type scale (1 = strongly disagree, 5 = strongly agree).

Intention was assessed with four items (Moon & Kim, 2001). Responses were recorded on a 5-point Likert-type scale (1 = strongly disagree, 5 = strongly agree).

4. Results

4.1. Quantitative data analysis

4.1.1. Difference analysis of participants' familiarity with the Palace Museum and VR technology

Participants' familiarity with the Palace Museum and VR technology, as measured by the questionnaire, was not found to vary significantly between groups. Specifically, analysis of questionnaire subscales returned the following results: "exposing to VR technology before" ($F(2) = 1.447$, $p = .248$), "visiting the Palace Museum before" ($F(2) = 0.405$, $p = .670$), "paying attention to the knowledge related to the Palace Museum" ($F(2) = 2.257$, $p = .118$). It indicated that the participants had similar backgrounds in their understanding of both VR technology and the Palace Museum.

It was found via Welch's *t*-test showed that there was no significant difference between the three groups in their knowledge of the Palace Museum ($p = .943$).

4.1.2. Effects of VR on the effectiveness of learning

There was no significant difference on the recall test ($p = .536$). As can be found in Table 3, there was a statistically significant difference in the score of the recognition test by participants between groups, as determined by one-way ANOVA analysis ($F(2) = 9.834$, $p < .001$).

A Bonferroni posthoc test revealed that the score of the recognition test was significantly higher in the desktop group ($M = 12$, $SD = 2.928$; $p = .002$) and the mobile group ($M = 12.57$, $SD = 3.275$; $p = .001$) conditions compared to the no-VR group ($M = 7.38$, $SD = 3.776$). The score in the desktop group and the mobile group is much higher than in the no-VR group as seen in Table 4. There was no significant difference between the desktop group and the mobile group ($p = 1.000$). It showed that using VR technology in digital museums can promote the effectiveness of learning. One possible implication of this is that using VR technology in digital museums can help users get knowledge and effectively improve the learning effect.

4.1.3. Differences between desktop and mobile VR interfaces

The independent *t*-test was used to analyze the UX of digital museums with different devices.

As seen in Table 5, in the aspect of users' perceptions, there was a significant difference in enjoyment ($t(27) = 2.349$, $p < .005$) and immersion ($t(27) = 2.669$, $p < .005$). To be more specific, the mobile group ($M = 3.57$, $SD = .576$) has a better enjoyment experience than the desktop group ($M = 2.87$, $SD = .974$); the mobile group ($M = 3.21$, $SD = .887$) has a stronger immersion experience than the desktop group ($M = 2.37$, $SD = .823$). There was no significant difference in presence ($p = .074$) and expectation ($p = .110$). But the same as the immersion experience, the mobile group ($M = 3.03$, $SD = .903$) had a higher presence experience than that of the desktop group ($M = 2.45$, $SD = .780$). On the whole, compared with the desktop group ($M = 2.95$, $SD = .851$), the mobile group ($M = 3.446$, $SD = .767$) had a higher expectation experience. Taken together, these results suggested that the digital museums on mobile had met users' expectations to a greater extent.

In the aspect of system usability, there was a significant difference in learnability between digital museums with different devices ($t(27) = 2.898$, $p < .005$). As seen in Table 6, the score of learnability of the desktop group ($M = 86.667$, $SD = 17.338$) was higher than that of the mobile group ($M = 64.286$, $SD = 64.286$). It shows that the function of desktop is easier to learn. What's more, the score of SUS and the score of usability in the desktop group ($M = 64.69$, $SD = 12.06$; $M = 59.196$, SD

Table 3
Results of one-way ANOVA analysis.

Group	*N*	Mean ± SD	*F*	*p*
Desktop group	15	12 ± 2.928	9.834	.000
Mobile group	14	12.57 ± 3.275		
No-VR group	13	7.38 ± 3.776		

Table 4
Bonferroni posthoc test between desktop/mobile/no-VR groups.

(I) Group	(J) Group	Mean Deviation (I-J)	*p*
Desktop group	Mobile group	−0.57	1.000
Desktop group	No-VR group	4.62	.002
Mobile group	No-VR group	5.19	.001

= 13.485) were higher than the mobile group (M = 57.628, SD = 18.932, M = 55.963, SD = 21.631). The findings of this study suggested that digital museum on desktop was easier to learn and use.

In the aspect of effectiveness of learning, attitude, and intention, there was a significant difference in attitude (t (27) = 2.231, p < .005) and intention (t (27) = 2.066, p < .005) between different devices (see Table 7). There was also a significant difference in the free browsing time after the first task (t (27) 2.703, p<. 005). The participants' attitude in the mobile group (M = 3.762, SD = . 619) was better than that of the desktop group (M = 3.178, SD = . 775). Their intention to use digital museums on mobile (M = 3.619, SD = . 726) was stronger than that of the desktop group (M = 2.956, SD = . 991). The free browsing time (M = 4.031, SD = 2.533) was longer than that of the desktop group (M = 1.886, SD = 1.408). One possible implication of this is that digital museums on mobile were more popular.

4.2. Qualitative data analysis

After the experiment, researchers interviewed the participants and asked them to talk about their perceptions (e.g., advantages and disadvantages) of the digital museums they viewed. By analyzing the data, researchers came up with the advantages and disadvantages of digital museums on desktop and mobile and the reasons for them. In line with the results of our quantitative data analysis, the immersion experience of the digital museums on mobile was better and participants were more willing to use it. Digital museums on desktop had advantages in terms of usability and learnability.

4.2.1. Analysis of the advantages of digital museums on mobile

The analysis showed that digital museums on mobile triggered higher immersion due to smooth operation. Portability is a key factor influencing users' intention to use them.

In terms of immersion, participants in desktop group felt that when they wanted to take a closer look at an attraction, manipulating it with the mouse did not feel smooth. Sometimes it required several clicks. Using the digital museums on mobile only required a touch screen swipe. "I wanted to go smoothly when browsing, but every time I used it, I felt that there were too many steps to click." "When the viewpoint moved inside a palace, I needed to tap to slowly move a section. The experience was not that smooth." Participants in mobile group said that virtual reality allowed users to get up close to artifacts as well as palaces that cannot be approached during field visits due to heritage protection. "There were some places I couldn't go in during the actual visit to the Palace Museum. I could see inside directly through this system. It had some better view perspectives, and the visual senses were pretty good." Previous research has shown that mobile allows users to click, move or slide using their fingers. More interaction may lead to the sensory depth (Yi, Wang, Tian, & Xia, 2021). As a result, digital museums on mobile have a greater sense of immersion.

At the level of attitudes and intention to use, participants in mobile

Table 5
Independent *t*-test analysis of users' perceptions.

Evaluation dimensions	Sub-dimensions	Groups	n	Mean	SD	*t*	*p*
Users' perceptions	Enjoyment	Desktop group	15	2.867	.974	2.349	.025
		Mobile group	14	3.571	.576		
	Immersion	Desktop group	15	2.367	.823	2.669	.013
		Mobile group	14	3.214	.887		
	Presence	Desktop group	15	2.45	.78	1.863	.074
		Mobile group	14	3.036	.903		
	Expectation	Desktop group	15	2.95	.851	1.652	.11
		Mobile group	14	3.446	.767		

Table 6
Independent *t*-test analysis of system usability.

Evaluation dimensions	Sub-dimensions	Groups	n	Mean	SD	*t*	*p*
System usability	SUS	Desktop group	15	64.69	12.06	1.189	.247
		Mobile group	14	57.628	18.932		
	Usability	Desktop group	15	59.196	13.485	.487	.63
		Mobile group	14	55.963	21.631		
	Learnability	Desktop group	15	86.667	17.338	2.866	.009
		Mobile group	14	64.286	23.948		

Table 7
Independent *t*-test analysis of effectiveness of learning, attitude, and intention.

Evaluation dimensions	Sub-dimensions	Groups	n	Mean	SD	*t*	*p*
Effectiveness of learning, attitude, and intention	Recognition test	Desktop group	15	12	2.928	.494	.625
		Mobile group	14	12.571	3.275		
	Recall test	Desktop group	15	6	4.209	.642	.527
		Mobile group	14	6.857	2.905		
	Attitude	Desktop group	15	3.178	.775	2.231	.033
		Mobile group	14	3.762	.619		
	Intention	Desktop group	15	2.956	.991	2.066	.049
		Mobile group	14	3.619	.726		
	Time	Desktop group	15	1.886	1.408	2.703	.011
		Mobile group	14	4.031	2.533		

group said that using their cell phones to visit museums was convenient and helped those who could not visit the museums on site. Therefore, they had a strong intention to use the digital museum and were willing to recommend it to their friends and relatives. "This applet was easy to use." "If it's my friends who can't go to the Palace Museum in person, I would recommend this system to them. The mobile applet is relatively easy to use." It could also explain why there was a greater attitude to use digital museums on mobile.

4.2.2. Analysis of the advantages of digital museums on desktop

The digital museum on desktop was more responsive and had a higher rating of usability. More cueing features were provided to the user. The score of learnability was higher.

At the usability level, users felt that the responsiveness of the system had a greater impact on usability. The presence of proper guidance in digital museums would enhance usability. Participants in mobile group said, "When I entered a new palace again, it was slow to switch. I didn't know if it was the lag of the system itself or because of the responsiveness of the phone nowadays. It reduced my experience."

Participants identified the lack of hints as the main factor affecting learnability of the system. The mobile screen weakened many toolbars and hid many hint functions because of its small size. To be more specific, the location of the map icon was small and the map hid most of the palace names. As a result, digital museums on mobile scored significantly lower than digital museums on desktop in terms of learnability. "It didn't prompt me. For example, I needed to explore the magnifying glass in the bottom right corner of the map on my own. When visiting the exhibits, there were no hints on how exactly to look at them." "It was a bit short on hints. Some small palaces inside the map that were not easy to find." The desktop interface was larger and provided a more detailed toolbar. The score of learnability was higher.

5. Discussion

This study evaluated the user experience of virtual reality interfaces in digital museums. With a comprehensive framework. With this framework, our study explored the usefulness of VR in promoting learning of digital museum users and compared the differences between desktop and mobile devices in providing VR experience.

5.1. A framework for evaluating digital museum VR interfaces

Combining Hassenzahl's model, CUX, and relevant previous research on digital museums in the literature, a framework was created for evaluating the cultural user experience of VR-based digital museums.

Compared to the studies that focused on specific evaluation dimensions of user experience (Loizides et al., 2014; Škola et al., 2020), our study has created a comprehensive and general theoretical framework. On one hand, our framework provides a comprehensive evaluation of digital museums along two dimensions: pragmatism and hedonism. It balances the educational and entertainment value of the museum while taking into account the characteristics of VR technology. On the other hand, for digital museums that offer VR experiences on multiple devices (desktop and mobile), this framework can help them gain a deeper understanding of the differences in user experience. Overall, the framework can provide comprehensive theoretical guidance for evaluation of user experience in VR-based digital museums.

5.2. The effect of VR on the effectiveness of learning in digital museums

For the second research question, this study found that participants in the VR group gained higher scores than the no-VR group in the recognition test significantly. It indicated that using VR technology in digital museums could enhance the effect of knowledge learning.

The advantages of adding VR technology in education have been demonstrated in many previous studies. Using VR in class can raise students' activeness (Liou & Chang, 2018) and get a sense of immersion (Shim et al., 2003), so as to obtain a better response. This study explored the application of VR in digital museums.

Previous studies have proved that using VR technology in physical museums could gain a better effect. Using VR technology in museums can enhance youth's interest in learning (Higgett, Chen, & Tatham, 2009). It can also improve users' participation and education in the process (Kang & Yang, 2020). However, previous studies have mostly relied on questionnaires to draw conclusions (Hsu, Liang, Chiou, & Tseng, 2018; Poce et al., 2019). It allows for quick data collection but lacks objectivity. In this research, a recall test and a recognition test are used to discuss the influence of VR technology on learning in museums. This study demonstrates that the above conclusions are also applicable to digital museums. VR provides information services for users from visual and auditory aspects. Its presentation forms are more abundant. It is likely that VR technology could stimulate users' interest, enhance their enthusiasm and create a sense of immersion. It ultimately achieved the effect of knowledge learning.

The findings of this study suggest that using VR technology in digital museums can also make users a sense of immersion, thus achieving the effect of knowledge learning.

5.3. Different user experience of the digital museum VR interfaces on different devices

For the third research question, this study reveals that digital museums with different devices would lead to different user experiences. Although some design rules apply to both desktop and mobile terminals, there are many differences in interface designing (such as sound and tactile output, single- or no-handed operation) (Gong & Tarasewich, 2004). Only a few comparative studies have used multiple devices with the same experience (André, 2019; Moro, Štromberga, & Stirling, 2017). The findings all indicate a direct impact of VR operation ease on user experience. User experience would be better with a system that is easier and smoother to operate. Similar to the results of previous studies, our study proves that when the participants browse on the mobile terminal, they would have a more immersive experience. Because the mobile device could be controlled by fingers. Using fingers is more convenient. It would influence their sense of immersion. Previous studies have also demonstrated that the mobile terminals allow users to click, move or slide using their fingers. More interaction may lead to sensory depth (Yi et al., 2021).

Similarly, the mobile group has a better enjoyment experience. When using the mobile device, the participants' attitude is better and their intention to use digital museums is stronger. Previous studies have shown that immersive feelings are closely related to human emotions. When users are immersed, they will feel positive emotions (Novak, Hoffman, & Yung, 2000). Therefore, the immersive feeling when using the digital museum will enhance their enjoyable experience.

According to the flow theory, when a person is completely immersed in an activity, the flow experience will improve the user's acceptance or loyalty to the product, and improve the user's satisfaction and intention to participate in the activity (Jiang, Chen, & Xu, 2021). Therefore, when users use digital museums on mobile, their senses of enjoyment and immersion are significantly better than using digital museums on desktop. Their attitude and intention are also significantly higher.

According to the findings, this study suggests that future development of digital museums should consider both pragmatism and hedonism. On the one hand, the digital museums on mobile provide a good experience and bring a higher intention to use. Therefore, the creation of digital museums on mobile will help the public pay attention to museums. In the future, the digital museum on mobile should be improved from the functional level. During the application of virtual reality, the performance issues of the system should be concerned. More features could be added to the system. For example, a beginner's guide, search functions, thumbnails, and user-friendly voice navigation can all add to

the better experience of a digital museum. On the other hand, for digital museums on desktop, museums could focus on using advanced technology to provide a more realistic experience. The current 360-degree panoramic technology applied by most digital museums does not meet the user experience well. Museums could consider adding technologies such as embodied interaction design to enrich the digital museum, which is also applicable to digital museums on mobile.

6. Conclusions

By combining the characteristics of CUX and VR technology, this paper evaluated the user experience of virtual reality interfaces in digital museums. This study contributed a comprehensive framework. Based on this framework, researchers explored the effect of VR technology on the effectiveness of learning and compared the differences of user experience of the digital museum VR interfaces with different devices. Our research shows that VR technology could promote the effectiveness of learning in digital museums. Furthermore, there are significant differences in user experience between digital museums on mobile and desktop devices. Digital museums on mobile are superior to digital museums on desktop in terms of enjoyment and immersion. The participants' attitude and intention to use are also stronger. It illustrates the importance of building digital museums on mobile and focusing on their user experience studies.

The theoretical contributions include three aspects. First, a comprehensive user experience framework was constructed, enabling a multidimensional evaluation of user experience in VR-based digital museums. Second, the limitations of traditional survey and interview methods were overcome by applying recall tests and recognition tests to quantify users' learning outcomes, leading to more objective conclusions. Third, we find that the user experience of digital museums based on different devices varies widely. Whether previous research on digital museums can be applied to digital museums on mobile exists uncertainty. Therefore, scientific research should also focus on the user experience of digital museums on mobile in the future.

The major findings of this study also have some general practical implications for the design of digital museum VR interfaces. Digital museums on mobile should focus on functional enhancements (such as adding search functions, thumbnails, and user-friendly voice navigation), while digital museums on desktop could focus on providing more realistic VR scenarios (such as considering embodied interaction design, 3D Modeling, etc. to enhance the realism of the system).

7. Limitations and future directions

This study has two major limitations that can be addressed in future work. First, a particular user group, i.e., the undergraduate or postgraduate students, was involved in the experiment. Digital museums are universal, so children, Digital museums are popular and universal, so children, middle-aged people and the elderly could be considered in the future. Second, the Likert scale was selected to obtain the subjective feelings of the participants. In the future, physiological indicators could be considered. The researchers plan to conduct a further experiment to include more heterogeneous participants and more measuring methods, in order to increase the generalizability of the findings.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This research has been made possible through the financial support of the National Social Science Fund of China under Grant No. 22&ZD325.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.dim.2023.100057.

References

Agostino, D., & Arnaboldi, M. J. A. H. (2021). From preservation to entertainment: Accounting for the transformation of participation in Italian state museums. *Accounting History, 26*(1), 102–122. https://doi.org/10.1177/1032373220934893

Anastasovitis, E., & Roumeliotis, M. (2023). Transforming computed tomography scans into a full-immersive virtual museum for the Antikythera Mechanism. *Digital Applications in Archaeology and Cultural Heritage, 28*, Article e00259. https://doi.org/10.1016/j.daach.2023.e00259

André, E. (2019). Viewing experience of augmented reality objects as ambient media-A comparison of multimedia devices. In *Ambient intelligence: 15th European conference, AmI 2019, Rome, Italy, november 13–15, 2019, proceedings* (Vol. 11912, p. 324). Springer Nature.

Arayaphan, W., Intawong, K., & Puritat, K. (2022). Digitalization of ancient fabric using virtual reality technology at the Wieng Yong House Museum: The FabricVR project. *Digital Applications in Archaeology and Cultural Heritage, 26*, Article e00233. https://doi.org/10.1016/j.daach.2022.e00233

Berkowitz, L., & Donnerstein, E. (1982). External validity is more than skin deep: Some answers to criticisms of laboratory experiments. *American Psychologist, 37*(3), 245–257. https://doi.org/10.1037/0003-066X.37.3.245

Bhattacherjee, A. (2001). Understanding information systems continuance: An expectation-confirmation model. *MIS Quarterly*, 351–370. https://doi.org/10.2307/3250921

Bozzelli, G., Raia, A., Ricciardi, S., De Nino, M., Barile, N., Perrella, M., … Palombini, A. (2019). An integrated VR/AR framework for user-centric interactive experience of cultural heritage: The ArkaeVision project. *Digital Applications in Archaeology and Cultural Heritage, 15*, Article e00124. https://doi.org/10.1016/j.daach.2019.e00124

Butler, A. C., & Roediger, H. L. (2007). Testing improves long-term retention in a simulated classroom setting. *European Journal of Cognitive Psychology, 19*(4–5), 514–527. https://doi.org/10.1080/09541440701326097

Carpenter, S. K., & Delosh, E. L. (2006). Impoverished cue support enhances subsequent retention: Support for the elaborative retrieval explanation of the testing effect. *Memory & Cognition, 34*(2), 268–276. https://doi.org/10.3758/BF03193405

Ch'Ng, E., Li, Y., Cai, S., & Leow, F. T. (2020). The effects of VR environments on the acceptance, experience, and expectations of cultural heritage learning. *Journal on computing and cultural heritage (JOCCH), 13*(1), 1–21. https://doi.org/10.1145/3352933

Coughlin, S. S. (1990). Recall bias in epidemiologic studies. *Journal of Clinical Epidemiology, 43*(1), 87–91. https://doi.org/10.1016/0895-4356(90)90060-3

Davis, C. G., Thake, J., & Vilhena, N. (2010). Social desirability biases in self-reported alcohol consumption and harms. *Addictive Behaviors, 35*(4), 302–311. https://doi.org/10.1016/j.addbeh.2009.11.001

Garzotto, F., Matarazzo, V., Messina, N., Gelsomini, M., & Riva, C. (2018). Improving museum accessibility through storytelling in wearable immersive virtual reality. In *2018 3rd digital heritage international congress (DigitalHERITAGE) held jointly with 2018 24th international conference on virtual systems & multimedia (VSMM 2018)* (pp. 1–8). IEEE. https://doi.org/10.1109/DigitalHeritage.2018.8810097.

Gong, J., & Tarasewich, P. (2004). Guidelines for handheld mobile device interface design. In *In proceedings of DSI 2004 annual meeting* (pp. 3751–3756).

Grier, R. A., Bangor, A., Kortum, P., & Peres, S. C. (2013). The system usability scale: Beyond standard usability testing. In *Proceedings of the human factors and ergonomics society annual meeting* (Vol. 57, pp. 187–191). Sage CA: Los Angeles, CA: SAGE Publications. https://doi.org/10.1177/1541931213571042. No. 1.

Guo, K., Fan, A., Lehto, X., & Day, J. (2021). Immersive digital tourism: The role of multisensory cues in digital museum experiences. *Journal of Hospitality & Tourism Research, 10963480211030319*. https://doi.org/10.1177/10963480211030319

Hack, M. (2016). *Museums: Educational or entertaining? Results from our first twitter poll.* Retrieved June 25, 2023 from https://museumhack.com/our-first-twitter-poll/.

Hall, A. (2009). Perceptions of the authenticity of reality programs and their relationships to audience involvement, enjoyment, and perceived learning. *Journal of Broadcasting & Electronic Media, 53*(4), 515–531. https://doi.org/10.1080/08838150903310468

Hammady, R., Ma, M., & Strathearn, C. (2020). Ambient information visualisation and visitors' technology acceptance of mixed reality in museums. *Journal on Computing and Cultural Heritage (JOCCH), 13*(2), 1–22. https://doi.org/10.1145/3359590

Hassenzahl, M., & Tractinsky, N. (2006). User experience-a research agenda. *Behaviour & Information Technology, 25*(2), 91–97. https://doi.org/10.1080/01449290500330331

Heyman, R. (1979). Comparative education from an ethnomethodological perspective. *Comparative Education, 15*(3), 241–249. https://doi.org/10.1080/0305006790150302

Higgett, N., Chen, Y., & Tatham, E. (2009). A user experience evaluation of the use of augmented and virtual reality in visualising and interpreting roman leicester 210AD (ratae corieltavorum). *Journal of Cultural Heritage, 10*(4), 520–528. https://doi.org/10.30958/ajhis.2-1-1

Hong, J. C., Hwang, M. Y., Chen, Y. J., Lin, P. H., Huang, Y. T., Cheng, H. Y., et al. (2013). Using the saliency-based model to design a digital archaeological game to motivate players' intention to visit the digital archives of Taiwan's natural science museum. *Computers & Education, 66*, 74–82. https://doi.org/10.1016/j.compedu.2013.02.007

Hsu, T. Y., Liang, H., Chiou, C. K., & Tseng, J. C. (2018). CoboChild: A blended mobile game-based learning service for children in museum contexts. *Data Technologies and Applications, 52*(3), 294–312.

Hu, W., Han, H., Wang, G., Peng, T., & Yang, Z. (2023). Interactive design and implementation of a digital museum under the background of AR and blockchain technology. *Applied Sciences, 13*(8), 4714. https://doi.org/10.3390/app13084714

Jiang, T. T., Chen, P. L., & Xu, Y. R. (2021). Research progress in the application of flow theory abroad. *Journal of Information Recording Materials, 11*(5), 4–16. https://doi.org/10.13365/j.jirm.2021.05.004

Kang, Y., & Yang, K. (2020). Employing digital reality technologies in art exhibitions and museums: A global survey of best practices and implications. *Virtual and Augmented Reality in Education, Art, and Museums, 2020*, 139–161. https://doi.org/10.4018/978-1-7998-1796-3.ch008

Kardes, F. R. (1996). Defense of experimental consumer psychology. *Journal of Consumer Psychology, 5*(3), 279–296. https://doi.org/10.1207/s15327663jcp0503_04

Konstantakis, M., & Caridakis, G. (2020). Adding culture to UX: UX research methodologies and applications in cultural heritage. *Journal on Computing and Cultural Heritage (JOCCH), 13*(1), 1–17. https://doi.org/10.1145/3354002

Konstantakis, M., Michalakis, K., Aliprantis, J., Kalatha, E., & Caridakis, G. (2017). Formalising and evaluating cultural user experience. In *Paper presented at the 2017 12th international workshop on semantic and social media adaptation and personalization (SMAP)* (pp. 90–94). IEEE. https://doi.org/10.1109/SMAP.2017.8022675.

Kuran, T. (1997). *Private truths, public lies: The social consequences of preference falsification*. Harvard University Press.

Li, P. P., & Chang, P. L. (2017). A study of virtual reality experience value and learning efficiency of museum-using shihsanhang museum as an example. In *2017 international conference on applied system innovation (ICASI)* (pp. 1158–1161). IEEE. https://doi.org/10.1109/ICASI.2017.7988391.

Liou, W.-K., & Chang, C.-Y. (2018). Virtual reality classroom applied to science education. In *Paper presented at the 2018 23rd international scientific-professional conference on information technology (IT)* (pp. 1–4). IEEE. https://doi.org/10.1109/SPIT.2018.8350861.

Loizides, F., El Kater, A., Terlikas, C., Lanitis, A., & Michael, D. (2014). Presenting cypriot cultural heritage in virtual reality: A user evaluation. In *Digital heritage. Progress in cultural heritage: Documentation, preservation, and protection: 5th international conference, EuroMed 2014, limassol, Cyprus, november 3-8, 2014. Proceedings* (Vol. 5, pp. 572–579). Springer International Publishing.

Lucas, J. W. (2003). Theory-Testing, generalization, and the problem of external validity. *Sociological Theory, 21*(3), 236–253. https://doi.org/10.1111/1467-9558.00187

McCaffery, J., Miller, A., Vermehren, A., & Fabola, A. (2015). The virtual museums of caen: A case study on modes of representation of digital historical content. In *Paper presented at the 2015 digital heritage* (pp. 541–548). https://doi.org/10.1109/DigitalHeritage.2015.7419571

Moon, J. W., & Kim, Y. G. (2001). Extending the TAM for a world-wide-web context. *Information & Management, 38*(4), 217–230. https://doi.org/10.1016/S0378-7206(00)00061-6

Moro, C., Štromberga, Z., & Stirling, A. (2017). Virtualisation devices for student learning: Comparison between desktop-based (Oculus Rift) and mobile-based (Gear VR) virtual reality in medical and health science education. *Australasian Journal of Educational Technology, 33*(6). https://doi.org/10.14742/ajet.3840

Museum, L. (2021). *The Mona Lisa in virtual reality in your own home*. Retrieved https://www.louvre.fr/en/what-s-on/life-at-the-museum/the-mona-lisa-in-virtual-reality-in-your-own-home. (Accessed 25 June 2023).

Novak, T. P., Hoffman, D. L., & Yung, Y. F. (2000). Measuring the customer experience in online environments: A structural modeling approach. *Marketing Science, 19*(1), 22–42. https://doi.org/10.1287/mksc.19.1.22.15184

Pantile, D., Frasca, R., Mazzeo, A., Ventrella, M., & Verreschi, G. (2017). New technologies and tools for immersive and engaging visitor experiences in museums: The evolution of the visit-actor in next-generation storytelling, through augmented and virtual reality, and immersive 3D projections. In *2016 12th International conference on signal-image technology & internet-based systems* (pp. 463–467). SITIS). https://doi.org/10.1109/SITIS.2016.78.

Poce, A., Amenduni, F., De Medio, C., Valente, M., & Re, M. R. (2019). Adopting augmented reality to engage higher education students in a museum university collection: The experience at roma tre university. *Information, 10*(12), 373. https://doi.org/10.3390/info10120373

Puig, A., Rodríguez, I., Arcos, J. L., Rodríguez-Aguilar, J. A., Cebrián, S., Bogdanovych, A., … Piqué, R. (2020). Lessons learned from supplementing archaeological museum exhibitions with virtual reality. *Virtual Reality, 24*, 343–358.

Rizvić, S., Bošković, D., Okanović, V., Kihić, I. I., Prazina, I., & Mijatović, B. (2021). Time travel to the past of Bosnia and Herzegovina through virtual and augmented reality. *Applied Sciences, 11*(8), 3711. https://doi.org/10.3390/app11083711

Schaufeli, W. B., Salanova, M., González-Romá, V., & Bakker, A. B. (2002). The measurement of engagement and burnout: A two sample confirmatory factor analytic approach. *Journal of Happiness Studies, 3*, 71–92. https://doi.org/10.1023/A:1015630930326

Schubert, T., Friedmann, F., & Regenbrecht, H. (2001). Igroup presence questionnaire. *Teleoperators Virtual Environ, 41*, 115–124.

Shim, K. C., Park, J. S., Kim, H. S., Kim, J. H., Park, Y. C., & Ryu, H. I. (2003). Application of virtual reality technology in biology education. *Journal of Biological Education, 37*(2), 71–74. https://doi.org/10.1080/00219266.2003.9655854

Škola, F., Rizvić, S., Cozza, M., Barbieri, L., Bruno, F., Skarlatos, D., et al. (2020). Virtual reality with 360-video storytelling in cultural heritage: Study of presence, engagement, and immersion. *Sensors, 20*(20), 5851. https://doi.org/10.3390/s20205851

Stroud, N. J. (2008). Media use and political predispositions: Revisiting the concept of selective exposure. *Political Behavior, 30*, 341–366.

Verhulst, I., Woods, A., Whittaker, L., Bennett, J., & Dalton, P. (2021). Do VR and AR versions of an immersive cultural experience engender different user experiences? *Computers in Human Behavior, 125*, 106951. https://doi.org/10.1016/j.chb.2021.106951

Wang, R. G., Dong, H. L., Wu, M. W., & Wu, Q. F. (2014). Research and design of digital museum based on virtual reality. In *Advanced materials research* (Vol. 926, pp. 2516–2520). Trans Tech Publications Ltd. https://doi.org/10.4028/www.scientific.net/AMR.926-930.2516.

Wiecko, F. M. (2010). Research note: Assessing the validity of college samples: Are students really that different? *Journal of Criminal Justice, 38*(6), 1186–1190. https://doi.org/10.1016/j.jcrimjus.2010.09.007

Wu, Y., Jiang, Q., Liang, H. E., & Ni, S. (2022). What drives users to adopt a digital museum? A case of virtual exhibition hall of national costume museum. *Sage Open, 12*(1), Article 21582440221082105.

Yi, M., Wang, Y., Tian, X., & Xia, H. J. S. (2021). User experience of the mobile terminal customization system: The influence of interface design and educational background on personalized customization. *Sensors, 21*(7), 2428. https://doi.org/10.3390/s21072428

Zeng, R. J. (2022). *An interactive study of dougong structure presentation based on VR hand movements (Master's thesis)*. Wuxi: Jiangnan University.

Zhang, C. (2005). *Modern psychology: The science of modern individuals exploring their own issues*. Shanghai People's Publishing House.

Zhang, D. (2015). *The effect of extraction difficulty and feedback timing on the effect of extraction practice (Doctoral dissertation)*. Fuzhou: Fujian Normal University.