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CubeMuseum AR: A Tangible Augmented Reality Interface for Cultural Heritage Learning and Museum Gifting

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ABSTRACT

Museum artifacts are the main way for visitors to experience and learn about cultural heritage. Augmented reality (AR) allows for high interactivity and is increasingly applied in museums to improve tourists' experience and learning. It also supports the extension of museum experience to outside of the physical museum space, contributing to the visiting trajectory and takeaway experience. In this paper, we present our design of two tangible AR interfaces for cultural artifacts: Postcard AR and CubeMuseum AR, followed by three user studies that evaluate and optimize the design. In *Study 1*, we conducted a within-subjects study ($N = 24$) that compares the two AR interfaces with a baseline condition (Leaflet). Our results demonstrate the positive effects of tangible AR interfaces on users' motivation and engagement in learning cultural heritage. In *Study 2*, we further explored how to optimize CubeMuseum AR by adopting a user-centered design approach. Through the analysis of expert interviews ($N = 7$) and an online survey ($N = 207$), the results specify a series of requirements and design guidelines for tangible AR interfaces to be used as a learning tool and a hybrid gift. Based on the findings, the design of the CubeMuseum AR was optimized and evaluated in *Study 3*. A between-subjects user study was conducted ($N = 32$) to compare the optimized design with the initial design. The results verified the positive effects of gamified tangible AR interfaces on users' motivation, engagement, and performance in learning cultural heritage. We present our design and evaluation results, and discuss the implications of designing tangible AR interfaces for cultural heritage learning and museum gifting.

1. Introduction

Augmented Reality (AR) interfaces are becoming increasingly accessible and pervasive to the public thanks to the ubiquity of portable devices such as smartphones and tablets. Previous studies have shown the potential to combine the strengths of digital affordances and tangible manipulations to enhance the learning experience for children (Li et al., 2019). Embodied metaphors in physical objects can afford intuitive interactions that are easy to learn, such as a steering wheel for a racing game (Horn, 2013). Similarly, effective manipulation and feedback allowed in tangibles facilitate user perceptions and assist user interactions with digital content (Pedersen & Hornbaek, 2011). For museums, touch-based interactions play a significant role in engaging users with historical artifacts. Previous research has shown the potential of AR to provide natural interactions, leading to the use of tangible AR (TAR) interfaces to engage visitors in tactile encounters (Dudley, 2012; Neale et al., 2011; Xu et al., 2022).

Within the domain of cultural heritage, many AR interfaces support the use of portable devices to interact with virtual information elsewhere, such as viewing an information label around an object using a smartphone. However, this is not a full integration of tangible user interface and AR, because there is a clear physical separation between the two. Bekele et al. (2018) argued that the full potential of TAR interface allows users to view the augmented information and interact with the augmented view through the physical object. That is, the augmented information is presented together with the physical object, rather than elsewhere. In addition, most AR interfaces support visitor experience within the museum, but few allow visitors to continue their experience after a museum visit. Although the use of tangible interactions in educational systems has shown to have a positive effect on learning (Azuma, 1997), there have been few studies that utilized a full integration of TAR interface in artifact learning outside of museums or investigated the effectiveness of TAR in learning cultural heritage. Motivated by the limited understanding of cultural heritage learning and museum takeaway experience with TAR, we ask two research questions: *how can TAR interfaces motivate, engage and support users in learning cultural heritage* (*RQ1*), and *how do users perceive the use of TAR interfaces for museum gifting* (*RQ2*)?

We propose two TAR interfaces for cultural artifacts: Postcard AR and CubeMuseum AR (see Figure 1). We compare them with a baseline condition (Leaflet) in *Study 1* ($N = 24$) to investigate users' motivation and engagement with TAR interfaces, and their learning of artifact information. Each participant used all three interfaces and provided

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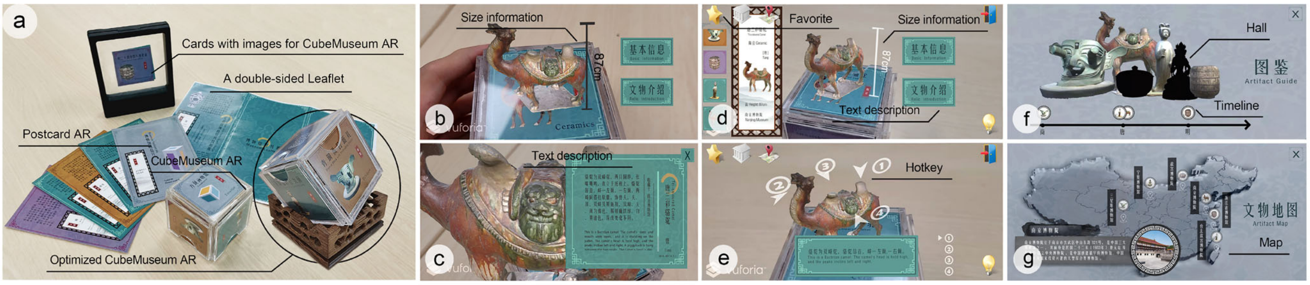


Figure 1. (a) Overview of two tangible AR interfaces (Postcard AR and CubeMuseum AR) and the baseline condition (Leaflet). (b) Initial CubeMuseum AR showing the 3D model an artifact, its size information, and (c) a rotated and zoomed-in view with text descriptions. (d) Optimized CubeMuseum AR showing the 3D model of an artifact, its size information, favorite collections, (e) information hotkeys, (f) timeline hall, and (g) map view.

their evaluations using questionnaires and interviews. The results indicated that participants were more motivated and engaged to learn when using CubeMuseum AR. This study confirms the potentials of TAR to support learning about cultural heritage. To obtain an in-depth understanding of TAR in cultural heritage learning and museum gifting, we adopted a user-centered design approach to optimize CubeMuseum AR in *Study 2*. We conducted expert interviews ($N=7$) and an online survey ($N=207$). The results indicated the value of gamification mechanisms in designing cultural heritage learning experiences, which bring to our *RQ3*: *how effective can gamified TAR interfaces motivate, engage and support users in learning cultural heritage*? To answer this question, we conducted a between-subjects design to compare the initial design and the optimized design in *Study 3* ($N=32$). The results demonstrated the positive effects of gamified TAR interfaces on users' motivation, engagement, and learning outcomes in learning cultural heritage.

Our research makes three main contributions. First, we introduce two TAR interfaces for museum takeaway experience and provide empirical evidence of the positive effects of TAR, especially gamified TAR on cultural heritage learning. It provides insights and facilitates discussion within the HCI community on how ubiquitous devices and interactive systems can be used to enhance museum learning experiences. The statistical analysis provides generalizable results for learning and education. Second, our evaluations of the initial and optimized CubeMuseum AR with both users and domain experts provide guidelines for the design and use of TAR interfaces in the museum context. These contribute to a better understanding of the practical value of the state-of-the-art research and promote a wider application of interactive technologies to the cultural and creative industries. Third, our discussions drawn from interviews and surveys reveal findings and unique insights that can be readily adopted by the HCI community for user experience design, and benefit museums and cultural institutions in the design of learning experiences with cultural artifacts, leading to increased public awareness of and interest in cultural heritage.

2. Related work

2.1. Tangible augmented reality

Tangible AR interfaces can allow the design of simple yet effective tools and operations to interact with virtual objects in AR environments (Billinghurst et al., 2008). They give users control over virtual information by allowing them to interact with physical items also. These tangible objects are usually marked with paper or cards that can be tracked in 3D space to locate virtual content (Neale et al., 2011). Using physical objects as a method of control can ease the difficulty in user operations as the manipulation of physical objects is often intuitive. The embodied control via tangible objects and responsive feedback can provide users a clear understanding of their actions (Havrez et al., 2016). For example, Kruszyński and van Liere (2009) used a printed tangible prop to represent corals and used a stylus to indicate locations on the surface. The printed tangible props support users' manipulation of the physical representation of scientific data in an intuitive way. Using tangible AR interfaces for teaching can motivate and facilitate learning activities. For example, complex chemistry knowledge can be transformed into vivid graphics with a physical cube as an exciting new avenue to learn (Chakraborty et al., 2014).

Tangible AR interfaces have been used in museums to support interactive experiences with cultural artifacts (Bekele et al., 2018). They represent a useful way to enhance a museum experience since they bridge the gap between physical and virtual information. Examples of tangible interfaces in museums include the use of touchscreens and physical replicas to enhance users' perceptions of museum artifacts (Short, 2015). Such tactile encounters support user interactions with museum artifacts with a direct approach (Marshall et al., 2016; Wojciechowski et al., 2004). In many cases, virtual content such as 3D models, videos, and audio recordings are superimposed on these tangible interfaces to introduce artifact information. This compensates for the fact that they cannot be touched and observed from different perspectives, and allows people to explore artifact knowledge through the rich digital affordances of multimedia (Mann & Fryazinov, 2019; Petrelli & O'Brien, 2018). For example, a recent study proposed a mobile XR tangible system that presents stereoscopic photographs using stereocards, which help evoke users' memories (Taipina & Cardoso, 2022). Similarly, the *Revealing Flashlight* employs a flashlight metaphor that allows users to illuminate part of a cultural artifact to observe the texture in detail (Ridel et al., 2014). These TAR interfaces well construct direct connections between real and virtual objects, providing a novel experience for cultural heritage learning. However, there is limited empirical evidence of the effects of TAR interfaces on users' motivation, engagement, and learning outcomes compared with a more traditional way of learning. It is also not clear if and how such interfaces support learning activities outside the museum spaces.

2.2. Motivation and engagement in learning

Ryan and Deci (2000) self-determination theory shows that learning outcomes can be improved by intrinsic motivation, which is defined as "doing something because it is inherently interesting or enjoyable." The facilitation of intrinsic motivation contributes to self-determined behavior, and this theory is widely applied in game-based learning to enhance the learning experience (Li et al., 2019; Miller et al., 1988). Previous work has addressed significantly the connection between motivation and learning activities. For example, motivation was identified as an important aspect in the usability evaluation of learning applications (Zaharias, 2006). It was shown that visual attractiveness, reading experience, and feedback are factors in users' learning motivation (Wang et al., 2020). Supporting user motivation is a significant design goal for cultural applications in that learning, either formal or informal, is always associated with the experience of cultural heritage.

In addition to motivation, engagement is also an important aspect of user experience. Engagement is identified as a major factor in the success of virtual heritage systems (Tost & Champion, 2007). Neale et al. (2014) study on virtual museum artifacts indicates that users are more likely to engage in learning if greater interactivity is supported. The authors found that users' inputs on a touchscreen and the system feedback help users concentrate on their learning. Games and digital visualizations have also been used to engage users in experiencing cultural heritage (Blumenstein, 2018; Liu et al., 2021). In the meantime, mobile technologies such as multimedia guides have become an important part of the museum experience. Othman et al. (2011) categorized the overall visitor experience, particularly visitor engagement into two parts: with an exhibition itself and with a multimedia guide. We are interested to see how users engage with TAR interfaces for cultural artifacts, and whether engagement contributes to their learning.

2.3. Gamification and visualization for learning

A growing body of research explores how to improve playfulness in learning activities. Gamified learning is an approach that attempts to transfer the motivational properties of games to learning activities (Dicheva et al., 2015). Such self-motivated learning is expected of museum experiences. Previous research has explored gamification mechanisms for museum learning. For instance, item collection was shown to be an effective strategy for learning as it gives users ownership of virtual items and a sense of achievement in the process, creating a rewarding cycle of emotional engagement through explorations (Cesário, 2019). Additionally, the sharing of personal collections further supports user engagement in social interactions (O'Hara et al., 2007). Similarly, employing puzzles to engage visitors as game players were found to be an effective way to support visitors' explorations and social activities within the museum space (Goodlander, 2009). These examples indicate possibilities for museums and cultural heritage experiences to incorporate gamification mechanisms to support playful learning experiences and social activities.

Similar to gamification, visualization is also an important approach to improving people's learning experience. Bach et al. (2018) summarized the effectiveness of 3D visualizations with different display technologies. They found that the 2D screen is better for comprehending locations, but the 3D projection is better for identifying the shape of objects. Furthermore, 3D visualizations have advantages in classification tasks and scenarios requiring tangible interaction. Meanwhile, stereoscopic perception is more significant than stereovision in improving learning effectiveness, meaning that some simple manipulations such as rotating, scaling, and moving the 3D depiction on the screen that supports stereoscopic perception are sufficient for learning activities with stereo images (Lu et al., 2022). Many researchers applied AR in information visualizations, making use of its stereo displays while maintaining users' awareness of the physical world (Bach et al., 2017; Walsh & Thomas, 2011). In the domain of cultural heritage, researchers have tried to augment digital visualizations onto physical museum artifacts using mobile devices (Blumenstein, 2018). This could make a rich array of data visible to users and enhance the museum experience. Li and Ch'ng (2022) also identified how the visualization and presentation of virtual objects inform the interaction design. Gamification and visualization combined with learning content can engage people in the learning process (Liang, 2020). However, further investigation is needed to learn how TAR interfaces could make use of them to support the learning of cultural heritage.

2.4. Museum takeaway experience and hybrid gifting

Museum experience can allow interaction with artifacts in ways that go well beyond simply visiting, and it does not end when visitors step out of the museum. Benford et al. (2009) argued that it should be a trajectory that extends over space and time and involves multiple roles and interfaces. Purchasing souvenirs and sending gifts are useful ways to continue visitors' coherent journey. Koleva et al. (2020) introduced the concept of hybrid gifts; that is, combining physical artifacts and experiences with digital interactivity to generate new kinds of gifts, such as wrapping physical gifts with digital media. Cultural artifacts in their digital forms would be a meaningful extension of visitors' museum visiting experience. A physical tangible with embodied virtual museum objects is a typical type of hybrid gift, which enables visitors' museum takeaway experience.

Falk (2016) identified five types of museum audiences: explorer, professional/hobbyist, experience-seeker, facilitator, and recharger. With different purposes for their museum visits, visitors have different expectations and preferences of the amount of serious information and playfulness in their

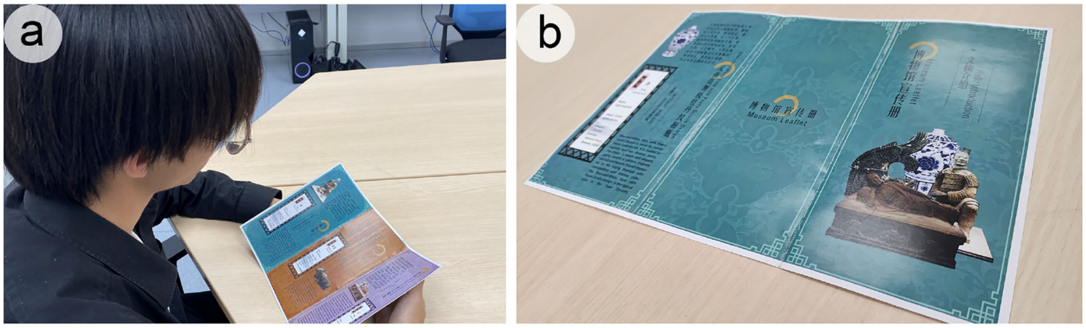


Figure 2. Demonstration of Leaflet: (a) a user using the Leaflet; (b) the physical Leaflet with text descriptions of artifacts.

onsite and takeaway experiences. Earlier we designed an AR prototype of embodied virtual museum (see Li et al., 2022). It overlays digital copies of cultural artifacts along with their stories and text descriptions to a physical cube, showing potentials to be used as a museum souvenir for visitors to take back home and continue their museum visiting trajectories. This kind of hybrid gift with digital interactivity acts as a replay interface that supports user reflections, discussions, and sharing of memories. In addition, allowing customization in a hybrid gift, either in the physical form or digital content, will support users' creation and sharing of personal experiences. From our early explorations of TAR for cultural heritage and related work on hybrid gifting, we foresee that TAR interfaces have great potentials to be used in museum gifting. This is currently an underexplored area that we aim to fill with this research.

3. CubeMuseum AR, Postcard AR, and Leaflet

In *Study 1*, we aim to investigate the effects of tangible AR interfaces in cultural heritage learning. Because our research interest is in the context of museum takeaway experience, we opted to design for mobile devices, instead of expensive head-worn devices such as HoloLens, to target a wider range of audiences. We implemented two TAR interfaces: Postcard AR and CubeMuseum AR. For a baseline comparison, we designed a Leaflet, which is currently the most common form of takeaway experience. In this section, we describe the design of each interface and detail the evaluation and results.

3.1. Interface design

3.1.1. Leaflet

Leaflet is arguably the most adopted approach in museums to present exhibition information. Based on the traditional paper medium, Leaflet presents users with an exquisite design with images and text information about cultural artifacts (see Figure 2). We created Leaflet using a commercially available image processing software, Adobe Photoshop. It has a size of 21×29.7 cm (A4) and adopts a threefold and double-sided design. Except for the front and back covers, each column of the Leaflet presents an image of a cultural artifact and its basic information, including the name, material, cultural period, affiliated museum, and a paragraph of text descriptions (see Appendix A).

3.1.2. Postcard AR

The design of Postcard AR is inspired by the Magic Book concept proposed by Billinghurst et al. (2001). They presented a prototype that includes a physical book with image targets and a piece of AR image recognition software. Users can scan the images on the book to trigger the corresponding digital information. We apply the Magic Book design to postcards, a common type of museum souvenir. A standard postcard size of 14.8×10 cm is used. Users can view an artifact image and read the text descriptions on the postcard. In addition, they can use a smartphone to view the augmented cultural artifact and its size information, and use touchscreen gestures to rotate and scale the object (see Figure 3). 3D models of museum artifacts were constructed using close-range photogrammetry and optimized for mobile device use following the workflow proposed by Chai and Li (2022).

3.1.3. CubeMuseum AR

CubeMuseum AR uses a cube with a size of 6 cm. The physical prototype consists of a wooden cube with six acrylic card slots, and some artifact cards with image targets (see Figure 4). The cards can be replaced and reorganized and thus allow for customization of the cube.

The virtual objects are presented to the user through a mobile AR application and a physical cube with image targets on the sides. Users can use a smartphone to scan a card and trigger the augmented information, including a 3D model of the cultural artifact and two buttons for size information and text descriptions (see Figure 5). The design of CubeMuseum AR follows the principle of embodied interaction (Dourish, 2001), which maps users' physical actions with the digital presentations and engages users in manipulating the physical cube. Users can interact with the cultural artifacts by rotating the physical cube. Touchscreen gestures are also allowed in CubeMuseum AR for users to rotate and scale the virtual artifacts. Users' making and communication of meaning are mediated in their purposeful actions with the tangibles.

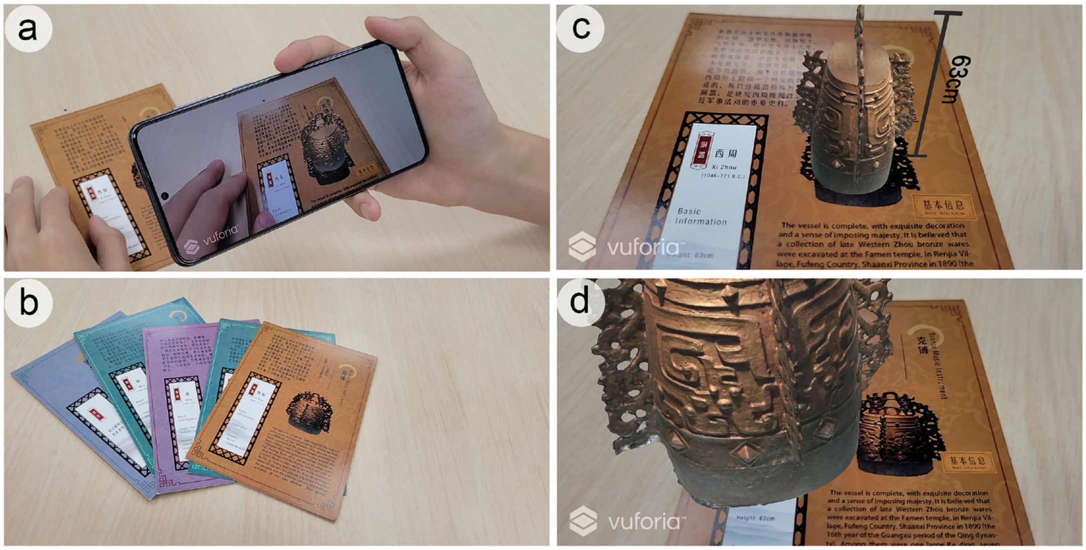


Figure 3. Demonstration of Postcard AR: (a) a user using the Postcard AR; (b) the physical postcards with text descriptions of artifacts; screenshots showing (c) the 3D model and size of an artifact, and (d) a zoomed-in view of an artifact.

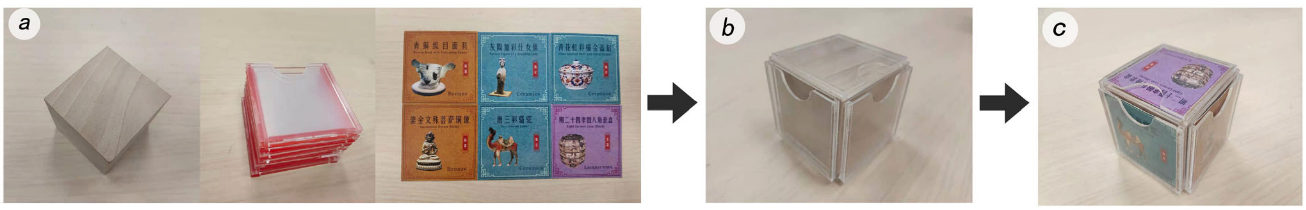


Figure 4. Physical prototype of CubeMuseum AR: (a) physical materials; (b) assembled cube; (c) assembled cube with artifact cards.

3.2. Evaluation

3.2.1. Study design

Study 1 is designed to answer *RQ1: how can TAR interfaces motivate, engage and support users in learning cultural heritage*? *RQ2* is also discussed in the interview. Based on the review of related work described in section 2.2, we have the following hypotheses in *Study 1*:

H1a. Users are more motivated when using TAR interfaces to learn about cultural heritage.

H1b. Users are more engaged when using TAR interfaces to learn about cultural heritage.

H1c. Users can achieve better learning outcomes when using TAR interfaces to learn about cultural heritage.

We adopted a within-subjects design across three conditions (Leaflet, Postcard AR, and CubeMuseum AR). Each participant experienced all three conditions, which were counterbalanced following a Latin Square design. The study received approval from the University Ethics Committee at the Xi'an Jiaotong-Liverpool University (#20-04-46).

3.2.2. Materials

Table 1 provides an overview of the three experimental conditions, including the physical materials and digital presentations used for each condition. We provided twelve cultural artifacts for three experimental conditions, with four objects for each condition. The artifacts images and information were collected from museums and the 3D models were constructed using the close-range photogrammetry technique. To facilitate a valid comparison, four different artifacts were used for each interface (see Appendix A for details). We used Unity and Vuforia SDK for the AR development. The applications were deployed on a Samsung Galaxy S21 smartphone. All surveys were hosted on our university survey platform based on LimeSurvey.

3.2.3. Participants

Twenty-four participants (12 males, 12 females) aged between 19 and 27 ($M = 22.04$, $SD = 2.074$) took part in the experiment. Participants were recruited from a local university and voluntarily signed up for the experiment. Most of our participants are Chinese (91.67%). Two third (66.67%) of them have limited museum visiting experience, with a frequency of either once or less than once a year. Attitude questions were rated from 1 (Strongly disagree) to 5 (Strongly agree). Participants showed a neutral attitude towards purchasing souvenirs in museums ($M = 2.67$, $SD = 1.27$). In terms of AR technology use, 16 participants have used AR, while 8 have not. In general, they are slightly

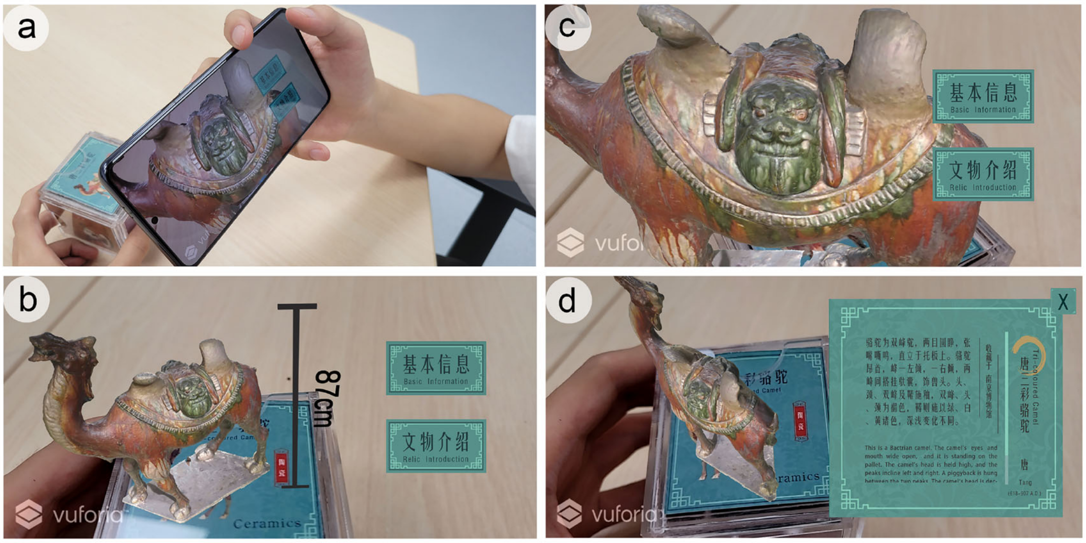


Figure 5. Demonstration of CubeMuseum AR: (a) a user using the CubeMuseum AR; screenshots showing (b) the 3D model and size of an artifact, (c) a zoomed-in and rotated view of an artifact, and (d) the text descriptions of an artifact.

Table 1. Overview of three experimental conditions.

	Physical materials		Digital presentations		
	Image, Name, Material	Text descriptions	3D model	Size information	Text descriptions
Leaflet	✓	✓	×	×	×
Postcard AR	✓	✓	✓	✓	×
CubeMuseum AR	✓	×	✓	✓	✓

familiar with AR ($M = 2.04$, $SD = 0.69$), and use 3D graphics with a moderate amount ($M = 3.29$, $SD = 1.16$).

3.2.4. Measures

The dependent variables in this study are motivation, user engagement, and learning outcomes. We measured them using the Intrinsic Motivation Instrument (IMI) (Ryan, 2006; Ryan & Deci, 2000, 2018), User Engagement Scale (UES) (O'Brien et al., 2018), and an Artifact Information Test (AIT), respectively.

Both the IMI and UES consist of four subscales, of which the descriptions are summarized in Table 2. We followed the original questionnaire structures and asked participants to rate the IMI on a 7-point Likert scale, and to rate the UES on a 5-point Likert scale.

In order to study the learning outcome, we adopted a pretest and posttest experimental design and asked participants to provide answers to the Artifact Information Test (AIT) that we prepared. By comparing participants' responses in the pretest and posttest, we determine how well each interaction interface improves participants' understanding of the cultural artifacts. Specifically, our design of the AIT allows us to measure users' learning of cultural artifacts from six dimensions, including History, Location, Material, Size, Feature and Description. Table 3 provides an example question for each dimension. We used single-choice questions in the test. Each question has one correct answer, three distractors, and an "I don't know" option. We prepared 3 questions for each artifact, resulting in 12 questions for each condition and 36 questions in total.

Table 2. Subscales and descriptions of Intrinsic Motivation Instrument (IMI) (Ryan & Deci, 2000) and User Engagement Scale (UES) (O'Brien et al., 2018).

	Subscale	Description
IMI	Interest/Enjoyment	Interest arouses the initiation and direction of attention and exploratory behavior, while enjoyment sustains the willingness to continue and persist in the activity (Meis et al., 2012).
	Perceived Competence	Perceived competence promotes people to set more difficult objectives to achieve, make more effort, and persist in challenges (Rodríguez et al., 2021).
	Perceived Choice	Perceived choice reflects the awareness of feelings and sense, which respect self behavior and awareness.
	Pressure/Tension	Pressure or tension causes positive effects like apprehension, which makes people feel less motivated.
UES	Focused Attention	Flow, specifically focused concentration, absorption, and temporal dissociation (Csikszentmihalyi, 2009).
	Perceived Usability	Users' effective (e.g., frustration) and cognitive (e.g., effort) responses to the system.
	Aesthetic Appeal	Users' perception of the visual appearance of a computer application interface (O'Brien & Toms, 2013).
	Reward	A set of items made up of endurability, novelty and felt involvement components (O'Brien et al., 2018).

In addition, we conducted semi-structured interviews with participants to discuss the advantages and disadvantages of the three interaction interfaces (*RQ1*), and the potential use of TAR for museum gifting (*RQ2*).

Table 3. Example questions for the six dimensions covered in the Artifact Information Test (AIT).

Dimension	Example Question
History	Which dynasty does the *Vajrasattva Bronze Statue* belong to?
Location	Where is the *Chinese Imari Covered Bowl With Floral Sprays* collected?
Material	What is the material of the *Eight Corners Case*?
Size	What is the correct size of the *Figure of an Assistant to the Judge of Hell*?
Feature	Which of the following feature is not mentioned or incorrect about the *Kneeling Arche*?
Description	Which of the following description is not mentioned or incorrect about the *Blue-and-White Vase with Peons Scrolls Design*?

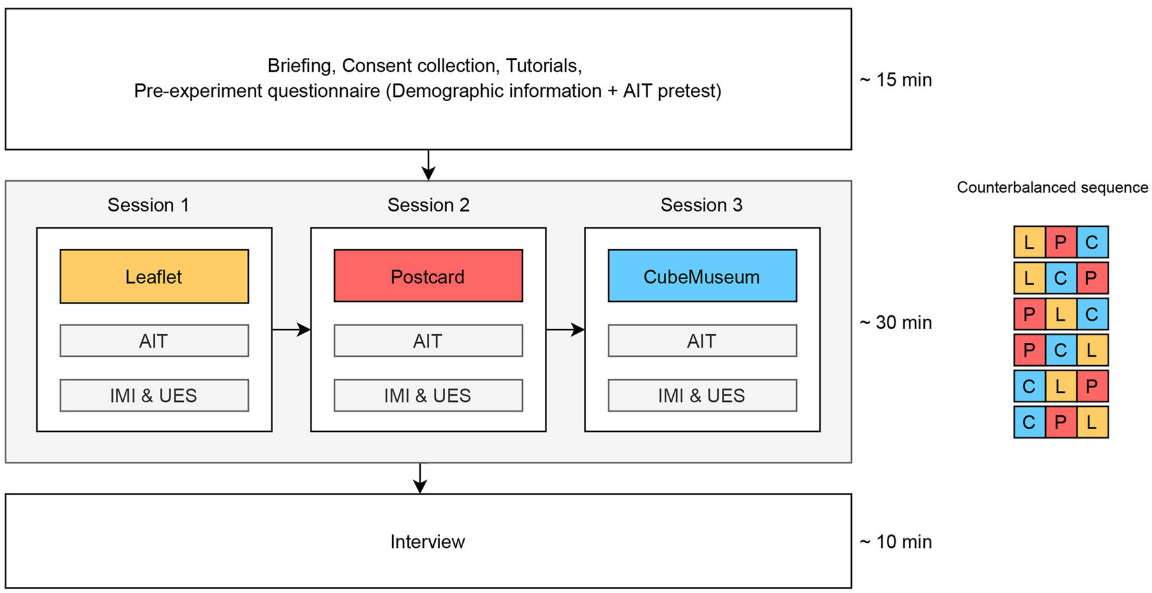


Figure 6. An example experimental procedure and the counterbalanced sequence of sessions. L: leaflet; P: postcard AR; C: CubeMuseum AR.

3.2.5. Procedures

Participants were briefed about the study at the start of each experiment. They were invited to read the information sheet and sign their consent. Prior to the experimental sessions, tutorials were provided for the two tangible AR interaction interfaces, with brief oral instructions given by the researcher. After the tutorial, participants were asked to complete the pre-experiment questionnaire, including demographic questions and the AIT pretest.

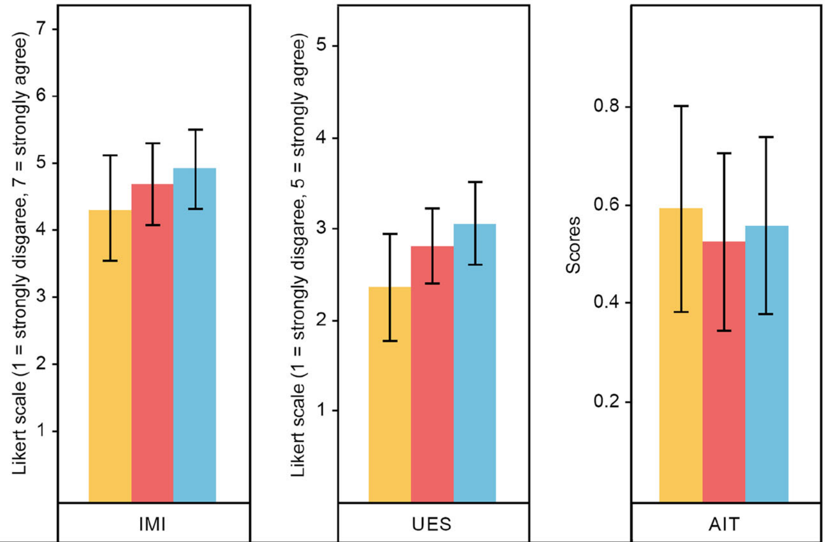
Our pilot studies showed that users spent about 3 min on average for each condition. Unobtrusive observations on participant interactions were performed throughout the three experimental sessions. The sequence of the three conditions was counterbalanced (see Figure 6). After completing each session, participants were required to complete two posttests: first the AIT posttest that measures the learning outcome, followed by the post-experiment questionnaire that measures intrinsic motivation and engagement. At the end of the experiment, participants were invited to interviews. Each experiment lasted about 55 min.

3.3. Results

We used IBM SPSS Statistics for the analysis. The subscales of the IMI for intrinsic motivation were found to be reliable (α ranged from 0.76 to 0.88), but some subscales of UES for engagement (focused attention, aesthetics, and reward) did not meet the suggested threshold (see Appendix G), thus need to be interpreted with caution. The data distribution of the post-experiment questionnaires was examined and the assumptions for parametric tests were ensured. One-way ANOVA was used for the comparison of questionnaire data rated on Likert scales. The differences between conditions were analyzed with Tukey's post-hoc test. AIT yielded scores of either 1 (correct) or 0 (incorrect) for each single-choice question. The mean score of participants' responses was calculated for the 12 questions (4 for each condition) and one-way ANOVA was performed to compare differences between three conditions. Figure 7 presents an overview of the questionnaire data analysis results. For qualitative data analysis, we conducted theme-based content analysis (Neale & Nichols, 2001) using NVivo. Interview transcription data were collated and grouped, using a matrix table showing raw data themes and summaries. Two researchers independently examined the data and identified themes emerged from the raw data. The researchers then discussed to reach an agreement on the summary themes. An additional researcher is consulted when there are any disagreements. Frequency counts were calculated and presented in the classification matrix to inform the discussions.

3.3.1. Intrinsic motivation

A one-way ANOVA showed that there was a statistically significant difference in intrinsic motivation between Leaflet, Postcard AR and CubeMuseum AR ($F(2,69)=5.030$,



	IMI	UES	AIT
Leaflet	4.29 (0.77)	2.35 (0.60)	0.59 (0.21)
Postcard	4.66 (0.60)	2.80 (0.41)	0.53 (0.18)
CubeMuseum	4.89 (0.58)	3.05 (0.44)	0.56 (0.18)

Figure 7. Means (with standard deviations) of the Intrinsic Motivation Instrument (IMI), User Engagement Scale (UES), and Artifact Information Test (AIT).

$p = 0.009$). Post-hoc tests indicated significant differences between Leaflet and CubeMuseum ($p = 0.007$). The differences between Leaflet and Postcard ($p = 0.132$), and between Postcard and CubeMuseum ($p = 0.463$) were insignificant. Users were more motivated when using CubeMuseum ($M = 4.86$, $SD = 0.58$) than using Leaflet ($M = 4.29$, $SD = 0.77$). Therefore, *H1a* is supported.

3.3.2. User engagement

A one-way ANOVA showed that there was a statistically significant difference in user engagement between Leaflet, Postcard AR and CubeMuseum AR ($F(2,69)$=14.105 $p < 0.001$). Post-hoc tests indicated significant differences between Leaflet and Postcard ($p < 0.001$), and between Leaflet and CubeMuseum ($p < 0.001$). The differences between Postcard and CubeMuseum were insignificant ($p = 0.377$). Users were more engaged when using CubeMuseum ($M = 3.05$, $SD = 0.44$) and Postcard ($M = 2.80$, $SD = 0.41$) than using Leaflet ($M = 2.35$, $SD = 0.60$). Therefore, *H1b* is supported.

3.3.3. Learning outcome

The analysis of the AIT showed no statistically significant differences between the three conditions in either the pretest ($F(2,69)$=.664, $p = 0.518$) or the posttest ($F(2,69)$=.755, $p = 0.474$). *H1c* is not supported. Nevertheless, paired-samples *t*-tests showed that the AIT posttest scores were significantly higher than the AIT pretest scores ($p < 0.001$).

Additionally, previous research showed that there is a significant correlation between learning motivation and outcome (Wu & Tai, 2016). We performed a correlation analysis to confirm this result and to investigate the role of engagement in learning. A Pearson correlation analysis was performed to determine the relationship between motivation, engagement and learning outcome. The results indicated that there were strong positive correlations between motivation and learning outcome (r = .259, $p = 0.028$), and between motivation and engagement (r = .767, $p < 0.001$). The correlation between engagement and learning outcome was statistically insignificant (r = .112, $p = 0.349$).

3.3.4. Time spent with each interface

Although we reminded users of the time at 3 min, we did not limit the time of use for each condition. A one-way ANOVA showed that there was a statistically significant difference in learning time between Leaflet, Postcard AR and CubeMuseum AR ($F(2,69)$ = 9.540, $p < 0.001$). Post-hoc tests indicated significant differences between Leaflet and Postcard ($p = 0.011$), and between Leaflet and CubeMuseum ($p < 0.001$). The differences between Postcard and CubeMuseum were insignificant ($p = 0.420$). Users spent more time on CubeMuseum ($M = 3.96$, $SD = 1.27$) and Postcard ($M = 3.50$, $SD = 1.32$) than using Leaflet ($M = 2.42$, $SD = 1.18$).

3.3.5. Observations and interviews

At the start of the interview, the researcher asked participants to rank the three interaction interfaces based on their subjective preferences. A Friedman test showed that there was a statistically significant difference in their ranking, χ^2 (2)=12.583, $p = 0.002$. Post-hoc analysis with Wilcoxon signed-rank tests was conducted with a Bonferroni correction applied, resulting in a significance level set at $p < 0.017$. There were no significant differences between Postcard and CubeMuseum (Z = −0.646, $p = 0.518$) or between Leaflet and Postcard (Z = −2.328, $p = 0.020$). However, the ranking for CubeMuseum was statistically higher than Leaflet ($Z = -3.258$, $p = 0.001$).

Qualitative analysis was conducted based on observation notes and audio transcriptions of the interviews. We adopted theme-based content analysis and summarized four themes in participants' evaluations of interaction interfaces: effectiveness, motivation, tangible manipulation, and presence (see Appendix B). While participants found the Leaflet to be very effective in learning, they also found it too ordinary to stimulate interest, suggesting that they might not have read it if not under the experimental conditions. On the contrary, they found CubeMuseum AR to be novel, attractive, and easy to learn. User's willingness to use technology is critical to learning activities (Elwood & MacLean, 2012), and the perceived effort expectancy is important for AR technology acceptance (Li et al., 2018). Furthermore, participants provided valuable insights in the use of TAR interfaces for museum gifting. Factors influencing users' choices on this are summarized into four themes: target group, digital design, physical material, and cost (see Appendix C). We discuss these evaluation findings next.

3.4. Study 1 discussion

During the interview, participants have provided their evaluations of the three interaction interfaces and also their justifications for some ranking and voting questions. These evaluations and justifications can be categorized into the following four themes as shown in Appendix B.

3.4.1. Learning effectiveness

We observed that although not specified or required, the efficiency of learning was an important determinant of some participants' rankings. For example, participant 9 ranked the highest on Leaflet because she found learning with Leaflet to be the most efficient. It presents all information about an artifact clearly on a single page. On the other hand, the displays and interactions with Postcard and CubeMuseum were less straightforward. Similar to the statistical results for learning outcome, participants' votes for the most effective interface for learning were balanced (CubeMuseum $N = 7$, Postcard $N = 10$, Leaflet $N = 7$). In addition, we found that learning efficiency is closely related to the preferred way of reading. Participants' responses showed that they prefer to read text information on paper, but are more willing to have interactive learning experience with the 3D objects on the touchscreen. A high degree of interactivity would increase the time in learning and thus affect the learning efficiency, but a low degree of interactivity will demotivate and disengage users. From a cognitive load perspective (Sweller et al., 1998), it is arguable that the two AR interfaces increased users' intrinsic load with the comparatively complex content and low prior knowledge. Users could have perceived higher extraneous load when they found some AR details interesting but overwhelming. On the other hand, users' germane load arises when they are engaged with the learning activities (Duran et al., 2022), which contributes to the learning effectiveness. Future design should consider how to trigger users' germane load to increase the efficiency in learning and maintain their learning motivation and engagement.

3.4.2. Motivation

Participants reported that CubeMuseum ($N = 17$) and Postcard ($N = 6$) motivated them the most in learning cultural artifacts because of the additional 3D information with the AR display, especially on size and feature. The statistical results on AIT also supported this point. Despite that AR motivated their learning, some participants ($N = 6$) still preferred Leaflet for learning, primarily because they were more concerned about learning efficiency, and they found reading texts on paper to be more acceptable than digital displays. We found that this is particularly true for participants who treated the experiment as a memorizing task. They found AR display and interactions complex whereas the classic way is more straightforward.

3.4.3. Engagement

Although the UES is a validated questionnaire to measure user engagement, it did not show reliable results in our study. One possible reason is that the questions are so general that participants provided different evaluations. Some evaluated the TAR interface while others assessed their engagement in the learning activities. Previous research showed that the learning engagement in an exhibition itself and the multimedia museum guide can be different (Na Ayudhya & Vavoula, 2017). To obtain a more reliable measure of user engagement in cultural heritage learning, it is necessary to clearly indicate the target of evaluation or to adopt context-specific measures, such as the Museum Experience Scale (Othman et al., 2011).

3.4.4. Tangible manipulation

Most participants reported that they like the tangible manipulations of CubeMuseum. We found that participants prefer rotating objects using the physical cube ($N = 15$) over touchscreen gestures ($N = 9$), indicating that tangible manipulations provide users with a more intuitive sense of control. Participants ($N = 4$) also liked that the cards are replaceable. The insertion and replacement of cards allowed more interaction possibilities as well as an increased degree of customization.

3.4.5. Presence

When asked "which interaction interface do you like for viewing an artifact," most participants ($N = 18$) voted for CubeMuseum, although it was not the only condition that presents 3D models in AR. Participants reported that the 3D models present more visual features of the artifacts, such as color and texture, which led to deeper impressions. Comparing CubeMuseum with Postcard, participants confirmed that they can better feel the size and features of an artifact with CubeMuseum. Participants also mentioned that being able to disable the text descriptions label was a bonus because it allowed a clear and undistracting view of an artifact.

3.4.6. Museum gifting

Participants commented that as an innovative product, CubeMuseum can be easily accepted by young people. 3D graphics and the novel tangible interactions with AR are the key factors for participants to favor the CubeMuseum, indicating the crucial role of digital design for participants to decide whether to buy this kind of hybrid gift. In terms of improvements in the physical design, some participants ($N = 5$) indicated that the wooden cube was too heavy, and lighter materials such as plastics will improve the tangible interactions.

3.5. Summary of findings from study 1

In this study, we found that users are more motivated and engaged in learning with tangible AR interfaces (CubeMuseum AR and Postcard AR) than with the baseline condition (Leaflet). The difference in learning outcome was insignificant. Based on our observations and interviews, we provide an in-depth analysis and discussions on participants' evaluations of these three interaction interfaces and their potential use for museum gifting. This study demonstrates the feasibility and practical value of TAR interfaces, and confirms the potentials of TAR in motivating and engaging users in learning about cultural heritage. Overall, CubeMuseum AR was shown to yield the best motivation and engagement in learning, and we see a potential opportunity to increase users' germane load with CubeMuseum AR to improve the learning effectiveness. Thus, we decide to further optimize the design and explore how to improve users' learning outcome with CubeMuseum AR.

4. Optimizing CubeMuseum AR

Study 2 aims to improve our understanding of *RQ1*, and to explore further on *RQ2*: *how do users perceive the use of TAR interfaces for museum gifting*? We adopted a user-centered design approach to better understand users' museum experience and the use of digital technologies. Potential stakeholders were invited to the following activities: (1) we interviewed domain experts in cultural heritage (CH) to obtain an in-depth understanding of their views on museum experience and CH learning, especially with the use of digital technologies; (2) we conducted an online survey that involved participants from different age groups and professions, aiming to understand and summarize user requirements of the general public to inform the optimization of CubeMuseum AR. Results from the interviews informed the design of the online survey and results from both activities ultimately guide the optimized design. The study is approved by our University Ethics Committee (20-04-46).

Table 4. Demographic information of domain experts.

ID	Gender	Year of work	Role
E1	Female	7 years	Museum Curator
E2	Female	3 years	Museum Operator
E3	Female	7 years	Exhibition Curator
E4	Female	4 years	Artist
E5	Male	6 years	Museum Director
E6	Female	3 years	Museum Volunteer
E7	Male	2 years	Lecturer in CH

4.1. Expert interview

To explore the feasibility of the use of TAR interfaces for museum learning and gifting experience, we invited domain experts to participate in a series of in-depth interviews.

4.1.1. Demographics

We interviewed seven experts (two males, five females, age $M = 30.71$, $SD = 6.34$), including practitioners and researchers who have worked in the domain of CH for at least 2 years. On average they have 4.57 years ($SD = 2.07$) of working experience (see Table 4).

4.1.2. Interview design

Participants were recruited using a snowball sampling technique. We first sent out invitations to our connections and our participants then introduced other interview candidates. All interviews were conducted by the same researcher, with necessary help from a moderator. The interviews took place in a face-to-face setting and were conducted in the participants' native language. We prepared a 50 RMB gift card for each participant to show our gratitude.

4.1.3. Procedure

At the beginning of each interview, we obtained informed consent from the participants and had some warm-up discussions. Informed by our research questions, the interview was semi-structured with five predetermined questions. We started with general questions about the role of museums and content curation, continued with more specific questions about learning and the use of technology, and followed by an evaluation of CubeMuseum AR. Each interview lasted around 90 min.

4.1.4. Data collection and analysis

All interview sessions were audio recorded using a Xunfei H1 recording pen. We used the auto transcription service provided by Xunfei. The interviewer double-checked the transcriptions to manually correct the errors. Two researchers analyzed the transcriptions independently and had a discussion to summarize the results. A summary of findings for each question is presented in the following sections.

4.1.4.1. How should the museum experience be curated for visitors?. From the first study, we learned that the design of tangible AR interfaces for cultural artifacts is a process of digital curation, which shares a lot in common with exhibition curation. Therefore, we asked this question to learn from experts' experiences.

Physical context is important for the curation of museum exhibitions. For instance, '*the exhibition layout, space, lighting, and ambient music should match the display of cultural artifacts*' (E3). In addition, we found that curators have tried to engage the audience using various forms of art, such as music, poetry, dance, animation, and film (E1, E5). "*Onsite workshops can also attract audiences because visitors like to have hands-on practices and unique experiences*" (E5).

Museum visitors have different roles. E5 commented that "*it is important for us to curate the exhibition to cater for different visitors' needs.*" Many visitors go to museums in small groups, spending their time with friends and families, wandering around, and having discussions. In this case, museum visiting is a social experience. Some visitors go to museums by themselves, expecting to enjoy alone time and some casual learning experience. E3 also mentioned that, "*some people just want to take some good photos in museums and post them on social media.*" This is the same for digital experiences: there are different roles, and even the same role of users will have different requirements and objectives in learning and socializing.

Informed by the answers, the curation of digital experience can combine various forms of media, such as texts, audios, videos, and animations to engage users. It is also important for the digital design to be aesthetically appealing, allow visitors to create their own experience, and suit different user characteristics and roles.

4.1.4.2. How to support the learning of cultural heritage?.

We asked this question to understand *RQ1* from experts' perspectives. E4 emphasized that "*the core of museum learning is to engage people through interactions about the physical exhibits*." Similarly, E3 and E5 said that museum learning can be driven by problem-solving, and through the use of technology, such as touchscreen tables, visitors can unconsciously acquire knowledge in fun.

Experts talked about the role of games in learning. E5 gave an example of a game project they did and commented that "*game-based learning attracts people who like to explore new things and deepens their memory through gamification elements. Such a way of learning is a combined effort that demonstrates the research outcomes of the scholars and the innovative ideas from the game designers.*"

Furthermore, this question also raised discussions on digital exhibitions and "at-home" learning. Participants found that online exhibitions will be a future trend, strongly driven by the long-lasting pandemic (E2, E5). When designing such exhibitions, E4 commented that "*the key information about museum artifacts, such as the period, material, and descriptions should be kept in the digital presentations.*"

Overall, answers to this question constantly addressed user interactions with technologies, games, and online platforms, providing insights to inform the design for CH learning.

4.1.4.3. What is your attitude towards digital technologies?.

The technological aspect of *RQ1* is further explored in this question. All participants see the advantage of digital technology in preserving CH. For example, E1 summarized that "*digital technology can help reconstruct artifacts and historical sites, with VR and AR, users can experience CH without the limitations of time and space.*"

Participants also reported that when used by visitors, digital technology can motivate people to learn. "*It can better promote cultural heritage because young people are more likely to get interested in it if technology is used*" (E6).

Despite the overall positive attitudes, participants also raised some concerns. For example, E5 reflected that "*I agree that there are many benefits of digital technologies, especially the metaverse and VR are very popular these days and I look forward to seeing our museum in that, but I doubt its effectiveness. The feelings you have when you see some artifacts are just so phenomenal and irreplaceable. With a virtual one, in the end, you'll know that it is fake.*"

Generally, the two benefits recognized for digital technologies are their affordances of interactive learning and learning outside the museums. Young people were identified as the potential target group of digital technology users. However, the benefits should not be overestimated. Digital technologies should be used to complement the physical museum visits, not as replacements.

4.1.4.4. How do you feel about CubeMuseum AR?.

We invited our participants to try and use CubeMuseum AR and Postcard AR to better understand *RQ2*. Constructive comments and criticisms were raised in the following aspects: target group, functional design, physical appearance, and cost.

Museum experts commented that they take into account a variety of factors when deciding what to include in the gift shop, and the target group is an important one. E7 stated that "*adults are more concerned about utility and aesthetics, while teenagers mainly care about whether the design is interesting enough.*" Interestingly, different target groups were identified for CubeMuseum AR. E3, E4, E5, and E6 said it could be used by young adults, whereas E1 and E2 found it better to target children and teenagers. They also mentioned that it is difficult to design one product that suits all age groups (E1, E2, E5, E7).

In terms of functional design, experts suggested adding more visualization elements to the application, such as interactive display of artifact information using timelines and maps (E1, E2), and more gamification mechanisms, such as the creation of personal collections and social sharing (E5). As discussed in section 4.1.2, they believe such a gamification approach can stimulate users' interest in learning by providing a playful experience.

For the physical appearance of museum gifts, E5 found the CubeMuseum AR heavy in hand and commented that the edges are too sharp to be used for children. E4 raised a standard as an artist, saying that "*cultural artifacts are works of art, so museum gifts should also show a sense of art, embody cultural values and be a nice decoration at home regardless of the utility.*" She further suggested combining some traditional Chinese patterns in the current physical product design.

In the meantime, cost is a major concern for museums to determine whether or not to include a product in the gift shop. E5 commented that although cost is usually not an issue for large museums with a great number of visitors, for smaller museums like them, they would prefer safer choices such as the Postcard AR, as it is cheaper and people can still use it without knowing what AR means.

Overall, experts are positive about the use of TAR interfaces as museum gifts. They like the genuine technological and innovative design, the vivid display, the intuitive control, the ability to customize it, and wish it could be more playful. E6 also commented that *"it can be used as a way to attract users and stimulate their interest in visiting those artifacts back in physical museums."* The interviews provided valuable insights, enhanced our understanding of *RQ1* and *RQ2*, and indicated directions for further optimization.

4.2. Online survey

We target the general public for our online survey to obtain a more comprehensive understanding of people's attitudes towards CH learning (*RQ1*) and museum gifting (*RQ2*).

4.2.1. Demographics

In total, we received 207 valid responses (101 males, 106 females) aged between 17 - 68 ($M = 30.77$, $SD = 9.88$). The two primary occupations of the respondents are students (38.31%) and professionals (24.38%). We also received responses from people working in different fields, as shown in Figure 8a. Most (78.26%) respondents hold a bachelor's degree or above.

4.2.2. Survey design

Aside from the four demographic questions (Q1–Q4), the main part of the survey consists of four parts: (1) AR experience (Q5–Q7), (2) museum experience (Q8–Q10), (3) cultural heritage learning (Q11–Q16), and (4) museum gifting (Q17–Q24). Some questions were inspired by Fu, Zhu, Xiao, Xu, and Ma's research (Fu et al., 2020) and also our expert interview results. The majority of the questions collect responses based on a 5-point Likert scale, others are multiple choice (Q12, Q13, Q17, Q19, Q21) and ranking questions (Q23).

4.2.3. Data collection and analysis

The online survey was created and distributed using LimeSurvey. The survey starts with an introduction of the research purpose and the collection of informed consent. Participants spent 4 min on average to complete the 23 questions in the survey. The survey was shared on social media and opened for 3 weeks. In total, we received 292 survey responses. 85 of them were incomplete, thus discarded in the data analysis, resulting in 207 valid samples. Data analysis was performed using IBM SPSS Statistics.

4.2.3.1. AR experience. From the results, we see that a third (32.36%) of respondents use 3D graphics at a moderate level or above. More than half (54.11%) of the respondents have used AR (Q6), and overall participants are slightly familiar with AR ($M = 2.43$, $SD = 1.06$) (Q7). Despite that people have some experience with AR, it is still a relatively new technology for the general public. However, for respondents aged between 18 and 30 ($N = 127$), the numbers are higher—they are somewhat familiar with AR ($M = 2.68$, $SD = 1.08$), and 46.46% of them use 3D graphics at a

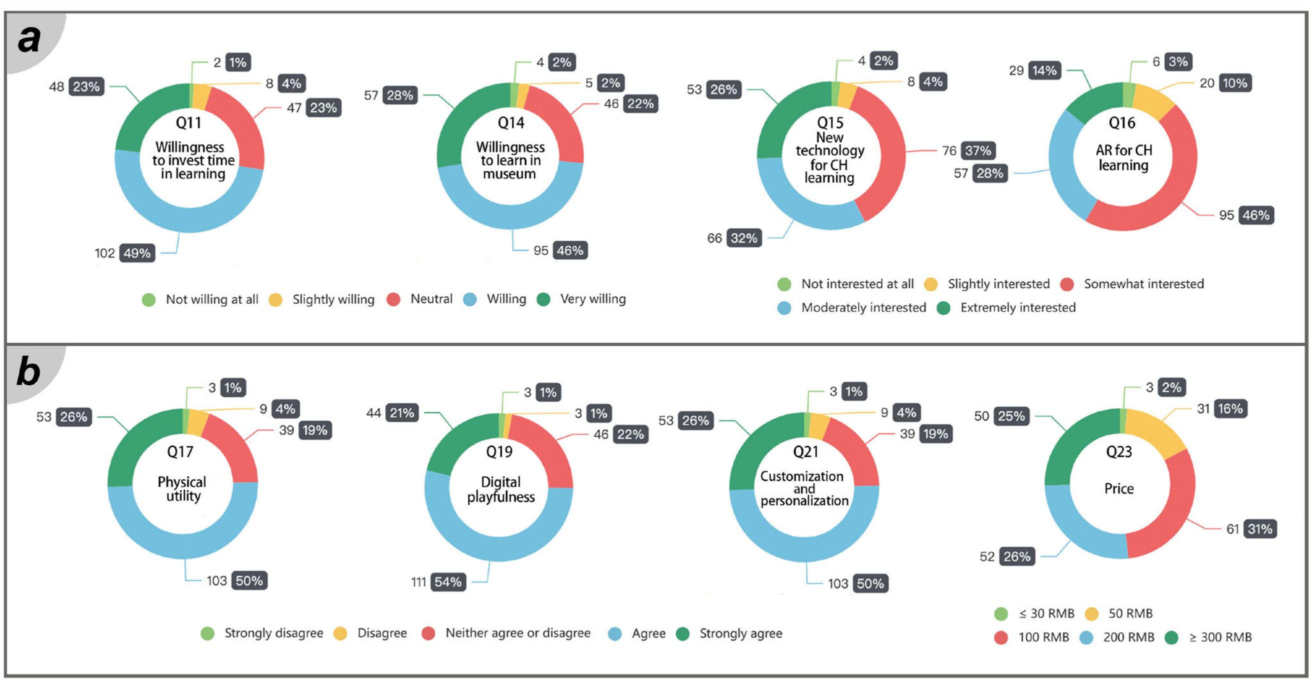


Figure 8. Survey results of (a) cultural heritage learning, and (b) museum gifting.

moderate level or above. These results indicated that young people tend to better accept new forms of media and adopt new technologies such as AR.

4.2.3.2. Museum experience. Almost all (93.76%) respondents have had museum visiting experience, and a third (33.82%) of them visit museums more than twice a year. In terms of the museum takeaway experience, 62.32% of respondents have purchased a museum souvenir (Q9), and more than half (57.01%) of them reported that they are likely or very likely to purchase souvenirs after a museum visit (Q10). Based on the results, we can see that museum visiting is an important part of people's lives, and the purchase of museum souvenirs is a significant part of museum experiences.

4.2.3.3. Cultural heritage learning. Most respondents reported that they are willing to invest time in learning ($M = 3.90$, $SD = 0.83$) (see Figure 8a, Q11), and most of them are willing to learn about cultural artifacts during museum visits ($M = 3.95$, $SD = 0.88$) (Q14). When asked about the learning source of CH information (Q12), mobile social media was the most selected choice (78.64%), followed by museums and exhibitions (60.68%). Specifically, Q13 showed that video is the most preferred way of learning (80.10%), followed by images (45.15%) and text (40.78%). With respect to the use of digital technologies for CH learning (Q15), more than half (57.48%) of the respondents are moderately or extremely interested to use new technologies in learning CH ($M = 3.75$, $SD = 0.95$). In particular, 45.89% of the respondents are somewhat interested in learning CH using AR ($M = 3.40$, $SD = 0.94$) (Q16). The results indicate that (1) learning is an inherent activity for museum visiting and CH experience, and (2) there are strong potentials for the use of AR in CH learning. Users' preferred source of information and way of learning also suggest ways in designing TAR interfaces, contributing to our understanding of *RQ1*.

4.2.3.4. Museum gifting. We asked specific questions to investigate the user of TAR interfaces for museum gifting (*RQ2*), and to verify the ideas and suggestions from *Study 1* and expert interviews. These include physical utility (Q17–Q18), digital playfulness (Q19-Q20), customization and personalization (Q21–Q22), and price (Q23–Q24). Figure 8b shows a summary of the Likert scale questions.

For the physical appearance, participants agree on the statement that *"I would like the museum souvenirs to have some utility functions (e,g. night light, music box, clock, weather broadcast, message board, etc.)"* ($M = 3.92$, $SD = 0.79$) (Q17). In particular, most participants prefer a traditional Chinese style (76.12%), compared to the hi-tech style (44.44%) and the modern minimalist style (44.93%) (Q18).

For the digital content, participants want the application to be playful in system design ($M = 3.78$, $SD = 0.78$) (Q19). Specifically, participants would prefer the use of multimedia (74.76%), such as audios, videos, and animations, followed by visual navigation (64.08%), such as maps and timelines, storytelling (63.16%), avatars (32.85%) and game rewards (31.40%) (Q20).

Inspired by experts' comments on effective museum curation practices (see section 4.1.1), we checked and found that participants like the idea of having a customized and personalized experience ($M = 3.94$, $SD = 0.87$). Participants are willing to take pictures and create an electronic postcard (70.05%), write personal notes (64.25%), and share their experiences on social media (46.86%) (Q22). In terms of the price for a museum souvenir, 51.78% of them accept prices of over 200 RMB (∼30 USD) (Q23).

A variety of factors for museum gifting were mentioned during the expert interviews, with cost, utility, appearance, and novelty as the primary ones. We asked participants to rank the importance of these factors in Q24. A Friedman test showed that there was a statistically significant difference in the ranking, χ^2 (3)=45.041, $p = <0.001$. The highest rank of the factors was appearance, followed by novelty, cost, and utility. Interestingly, utility, while deemed as important in Q17, is ranked the last in this question. This ranking is, however, in line with E4's comments in section 4.1.4, addressing the importance of appearance and the sense of art.

4.3. Summary of findings from study 2

Study 2 adopted a user-centered design approach with a series of interviews with domain experts and an online survey with the general public. With expert interviews ($N = 7$), we learned the importance of learning in cultural heritage experience and obtained inspirations for digital curation, such as supporting different roles and personalized experiences. We also understand better the role of digital technologies, such as games and online platforms, in CH learning. Experts' evaluations of CubeMuseum AR also provided some ideas that were further explored in the online survey. The survey ($N = 207$) showed that when using TAR for CH learning, participants care the most about two things: the playfulness of the digital content and the aesthetics and novelty of the physical product design. Specifically, (1) young people are more familiar with 3D graphics and AR technology, so it would be beneficial to target this age group for the adoption of TAR interfaces; (2) there are great values in designing innovative souvenirs and gifts for museum takeaway experience because many visitors are willing to purchase them and have enough budget (∼200 RMB or ∼30 USD); (3) AR should take advantage of its mobile platform, multimedia presentations, and innovative technological controls to support users' learning of cultural heritage; (4) when being used for museum gifting, ideally a TAR interface should be playful, allow for customization and personalization, have an appealing appearance, be novel in design, have a reasonable price and also some physical utilities. We will explore these findings in *Study 3*. Both expert interviews and the online survey indicated that young people are the most appropriate target group for TAR interfaces. The results and findings were taken into account to optimize CubeMuseum AR, which is described and evaluated in the next section.

5. Optimized CubeMuseum AR

From the previous study, we obtained a comprehensive view of cultural heritage learning and museum gifting from both the expert and the public. A set of design requirements and ideas were summarized for TAR-based learning and museum gifting. To address the previous findings and to obtain concrete optimization approaches, we held a design workshop with 12 participants (5 females, 7 males, age $M = 21.58$, $SD = 1.62$), divided into two groups of six. Two groups worked independently to brainstorm ideas for (1) playfulness in the digital design and (2) aesthetics in physical appearance. Participants' prototype designs demonstrate optimization towards the use of audio introduction, music, animation, map, storytelling, and some collection strategies. One group proposed artwork creation as an approach for emotional engagement with artifacts; the other group allowed users to share their experiences via social media. Both groups used wooden materials and adopted some Chinese traditional patterns for an optimized appearance.

Here we introduce the optimized design of CubeMuseum AR, and present a comparative evaluation (*Study 3*) of the optimized design and the initial design. This study contributes to our understanding of *RQ2* and *RQ3*.

5.1. Design

The optimized CubeMuseum AR aims to improve the learning effectiveness and the museum takeaway experience. From our findings in the previous two studies, we decided to target young people for the optimized design. We improved the digital design using gamification mechanisms and enhanced the physical design with user-inspired solutions. Table 5 shows an overview of improvements in the optimized design.

5.1.1. Physical design

The physical design of CubeMuseum AR was improved in terms of its appearance and weight. As the initial design was found heavy (about 210 g), we replaced the solid wooden cube with a hollow acrylic cube (see Figure 9) and reduced the weight to 75 g. We also added a wooden base with traditional Chinese patterns to improve its aesthetic look when not used.

5.1.2. System design

We improved the system design of CubeMuseum AR based on the lessons gathered in the previous studies: to consider different roles, to allow for playfulness (To Play), to facilitate learning with game elements (To Learn), and to support personalized experience (To Create).

5.1.2.1. To play. Similar to the initial design, users can manipulate the cultural artifacts using direct manipulation of the physical cube or touchscreen controls. Users can add an artifact to their favorite collection. A discovering animation is played when the artifact is collected (see Figure 10a). Artifacts in a user's favorite collection can be viewed at any time without using the physical cube (see Figure 10b). In addition to the 3D model, size information, and text descriptions, an audio guide option is provided as an alternative approach to obtain artifact information (see Figure 10c). These gamification mechanisms allow users to play with CubeMuseum AR. For users with clear learning objectives, they can switch into "To Learn" mode by clicking on the bulb icon at the right bottom corner.

5.1.2.2. To learn. To better support users' learning with cultural artifacts, we adopted some visualization methods. First, the information label is replaced with information hotkeys (see Figure 11a). By clicking on the numbers around the

Table 5. Overview of improvements of the optimized CubeMuseum AR.

Physical design		System design		
Weight	Materials	Digital presentations	Visualizations	Gamifications
	Wooden cube,	Audio guide	Information hotkeys	Item collection
210 g	acrylic slots	Animations	Timeline hall	Photo-taking
→	→ Acrylic cube,	–	Map view	Social sharing
75g	wooden base	–	–	Storyboard

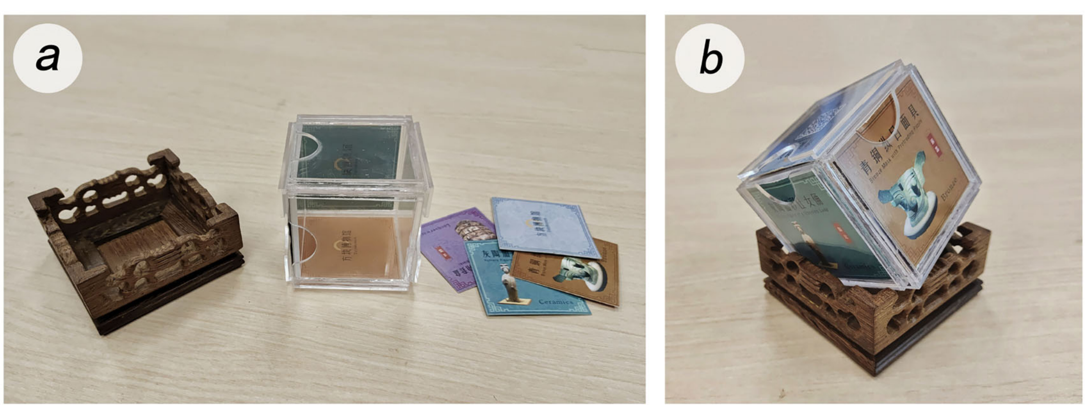


Figure 9. Optimized physical prototype of CubeMuseum AR: (a) physical materials; (b) assembled cube with artifact cards and a wooden base.

Figure 10. To Play in CubeMuseum AR: (a) an artifact showing up after a discovering animation; (b) 3D model of an artifact and buttons for size information and descriptions, the left side menu showing the favorite artifacts; (c) information label with an audio guide option.

Figure 11. To Learn in CubeMuseum AR: (a) information hotkeys; (b) timeline hall; (c) map view.

Figure 12. To Create in CubeMuseum AR: (a) photo-taking; (b) gallery and social sharing; (c) storyboard with personal notes.

artifact, users can view a detailed introduction of the corresponding features. In addition, users can view their favorite collections in two ways: a timeline hall and a map view. The timeline hall presents collected items in color and the uncollected in shadow (see Figure 11b). Artifacts are presented in their relative size and arranged from left to right based on the time period they belong to, making the size information more perceptible and the historical time sequence more memorizable. With the map view (see Figure 11c), users can have an overview of the artifact locations and access the museum details. This facilitates users' learning of geographical information.

5.1.2.3. To create. As personalized experience was shown to be important in *Study 2*, we include some game mechanisms to allow users to create. First, users can take photos with 3D artifacts in view (see Figure 12), allowing them to put the artifacts in different backgrounds and create artworks. These photos can be stored in the gallery, saved to the local album, or shared on social media. The system also prompts users to write personal notes to the storyboard. The design builds a connection between the artifacts and users' personal meaning making process, contributes to a personalized experience, and satisfies users' social needs.

5.2. Evaluation

5.2.1. Study design

Study 3 is designed to investigate *RQ3*: *how effective can gamified TAR interfaces motivate, engage and support users in learning cultural heritage*? The following hypotheses are drawn from related work (see section 2.3):

H3a. Users are more motivated when using gamified TAR interfaces to learn about cultural heritage.

H3b. Users are more engaged when using gamified TAR interfaces to learn about cultural heritage.

H3c. Users can achieve better learning outcomes when using gamified TAR interfaces to learn about cultural heritage.

We conducted a between-subjects user study with 32 participants to compare the optimized design (CubeMuseum+)

Table 6. Subscales and descriptions of Museum Experience Scale (MES) and Multimedia Guide Scale (MMGS) (Othman et al., 2011).

Subscale		Description
MES	Engagement	The concept of engagement is often used to describe visitors' enjoyment of interactive activities that will make their museum time enjoyable.
	Knowledge/Learning	Knowledge or learning is the thing that visitors can gain from the exhibits/exhibitions.
	Meaningful Experiences	Meaningful experiences express the process of getting positive knowledge or skills from doing, seeing, or feeling things.
	Emotional Connection	An emotional connection is a subjective experience that combines to form a bond between visitors and exhibitions.
MMGS	General Usability	General usability of the multimedia guide is used to measure its appropriateness and ease of use in the museum experience.
	Learnability and Control	Learnability and control refer to whether the guide is simple to use, whether the user feels in charge and whether the information is presented in a meaningful manner.
	Quality of Interaction with the Guide	Quality of interaction with the guide is generally regarded as part of usability or user experience, and it also to the ability of the guides to respond to the user's actions. (Othman et al., 2013)

with the initial design (CubeMuseum). Participants were randomly allocated to each of the two conditions. The study is approved by our University Ethics Committee (20-04-46).

5.2.2. Materials

To facilitate a valid comparison, the same six artifacts were used for both the initial and the optimized interface (see items 1, 4, 5, 8, 10, and 12 in the Appendix F for details). Like the initial design, we used Unity and Vuforia SDK for developing the AR application. The applications were deployed on a Samsung Galaxy S21 smartphone. Questionnaires were hosted on our university survey platform based on LimeSurvey.

5.2.3. Participants

Thirty-two participants (16 males, 16 females) aged between 19 and 26 ($M = 20.75$, $SD = 2.125$) took part in the experiment. All participants voluntarily signed up for the experiment. The majority of our participants visit museums once or less than once a year (62.5%). Attitude questions were rated from 1 (Strongly disagree) to 5 (Strongly agree). Participants showed a neutral attitude towards purchasing souvenirs in museums ($M = 2.93$, $SD = 1.01$). In terms of AR technology use, 20 participants have used AR, while 12 have not. In general, they are slightly familiar with AR ($M = 2.18$, $SD = 0.93$), and occasionally use 3D graphics ($M = 2.71$, $SD = 1.20$).

5.2.4. Measures

The dependent variables in this study are motivation, user engagement, and learning outcomes. We measured them using the Intrinsic Motivation Instrument (IMI) (Ryan, 2006; Ryan & Deci, 2000, 2018), Museum Experience Scale (MES) and Multimedia Guide Scale (MMGS) (Othman et al., 2011), and an Artifact Information Test (AIT).

Instead of examining the general user engagement as we did in *Study 1*, we adopted MES and MMGS to study users' engagement with guide systems within museum-related contexts. Both the IMI and MES consist of four subscales, and the MMGS consists of three subscales, of which the descriptions are summarized in Table 6 (see also Table 2 for IMI). We followed the original questionnaire structures and asked participants to rate the IMI on a 7-point Likert scale, and to rate the MES and MMGS on a 5-point Likert scale.

Similar to *Study 1*, we adopted a pretest and posttest experimental design and asked participants to provide answers to the AIT to measure learning outcome (see section 3.2.4). This AIT consists of 18 questions in total, 12 single-choice questions (2 for each artifact), and 6 other types of questions including multiple-choice, ranking, and fill-in-the-blank questions as shown in Figure 13. These six questions measure the six artifact dimensions (as detailed in Table 3), and the choices of each question involve information about multiple artifacts. The inclusion of different question types is to reduce the possibility of false positives in single-choice questions, thus ensuring a more accurate measure of learning outcomes.

We constructed a semi-structured interview with three parts: the strengths and weaknesses of CubeMuseum AR for learning cultural heritage (*RQ1*); the playfulness of CubeMuseum AR and suggestions for improvements (*RQ3*); the use of CubeMuseum AR as a hybrid museum gift and its potential context of use (*RQ2*).

5.2.5. Procedures

Similar to *Study 1*, we introduced our study to participants and asked for their consent, followed by a tutorial on the use of CubeMuseum AR. After the tutorial, participants were asked to complete the pre-experiment questionnaire, including demographic questions and the AIT pretest.

Participants used either the initial or the optimized CubeMuseum AR for the experimental session under unobtrusive observations. After that, participants were asked to complete the AIT posttest and the post-experiment questionnaire that measures intrinsic motivation and engagement. At the end of the experiment, participants were invited to interview evaluations of CubeMuseum AR in its use for (1) learning, (2) playing, and (3) gifting. Each experiment lasted about 50 minutes (see Figure 14).

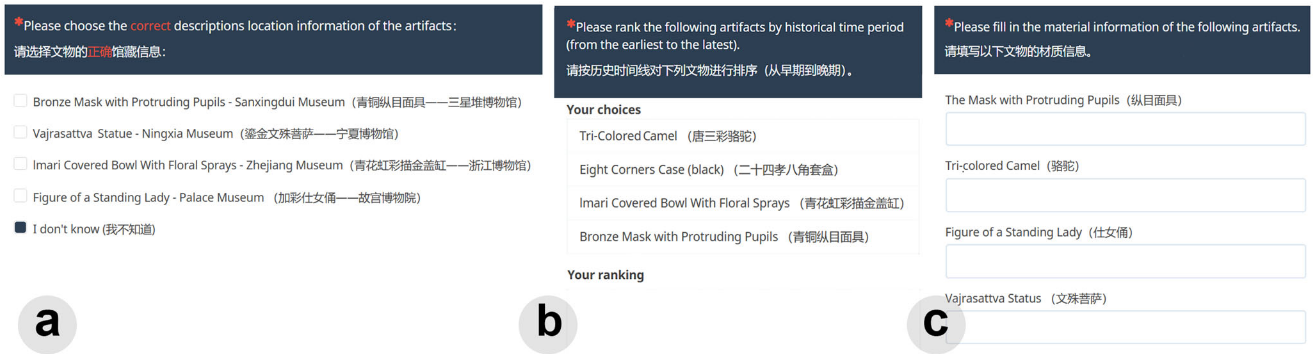


Figure 13. Examples of (a) multiple-choice question (select all that apply), (b) ranking question, and (c) fill-in-the-blank questions used in AIT.

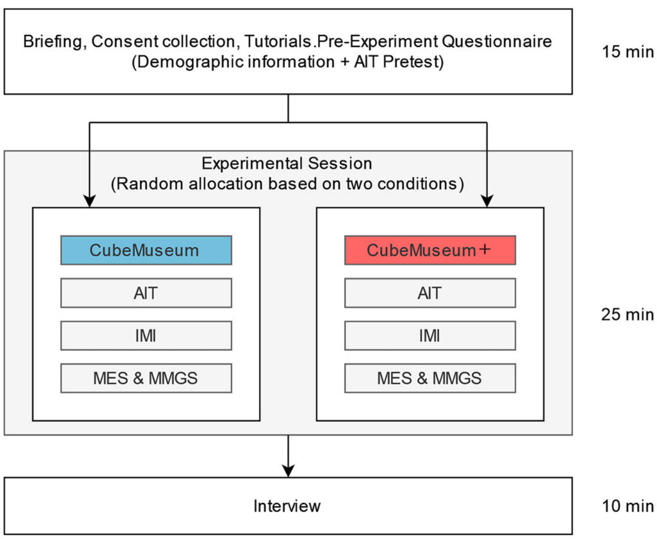
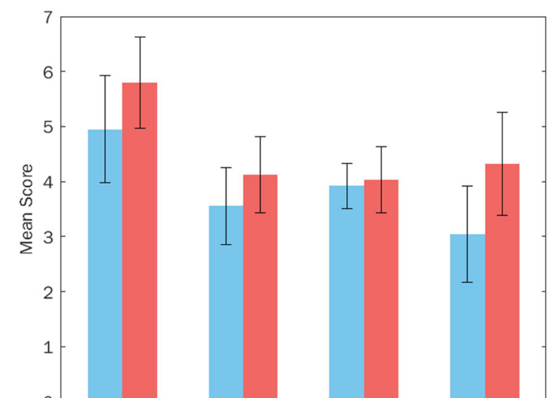
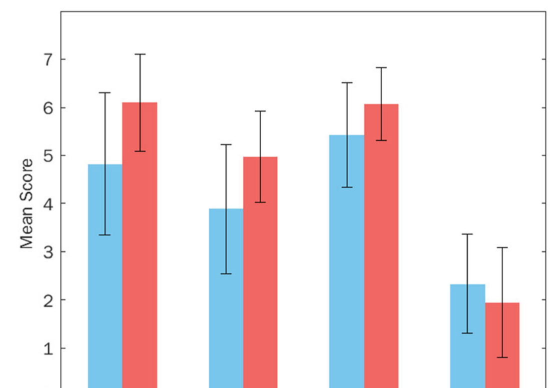


Figure 14. An example experimental procedure.



	IMI	MES	MMGS	AIT
CubeMuseum	4.95 (1.00)	3.55 (0.70)	3.92 (0.41)	3.04 (0.87)
CubeMuseum+	5.80 (0.83)	4.12 (0.70)	4.03 (0.60)	4.32 (0.94)

Figure 15. Means (with standard deviations) of the Intrinsic Motivation Instrument (IMI), Museum Experience Scale (UES), Museum Multimedia Guide Scale (MMGS), and Artifact Information Test (AIT).



	IE	PCO	PCH	PT (R)
CubeMuseum	4.82 (1.48)	3.89 (1.34)	5.43 (1.09)	2.34 (1.03)
CubeMuseum+	6.10 (1.01)	4.97 (0.95)	6.06 (0.76)	1.95 (1.14)

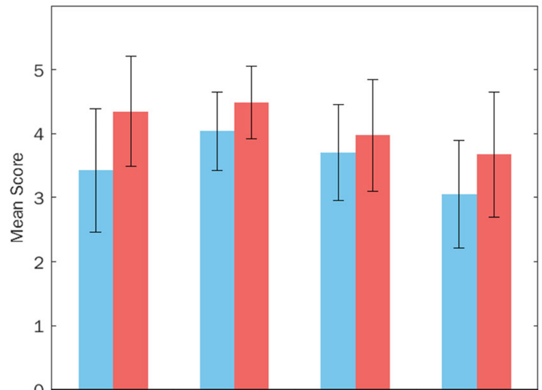
Figure 16. Means (with standard deviations) of the Interest/Enjoyment (IE), Perceived Competence (PCO), Perceived Choice (PCH), and Pressure/Tension (PT) in Intrinsic Motivation Instrument (IMI).

5.3. Results

We used IBM SPSS Statistics for the analysis. The reliability of the motivation and engagement questionnaire measures was assessed and indicated by Cronbach's alpha. All measures were found reliable (α ranged from 0.76 to 0.88, see Appendix G). The distribution of data was analyzed using the Shapiro-Wilk test. Welch's t-test was used to analyze data that distribute normally and the Mann-Whitney U test was used otherwise. AIT yielded scores of either 0 (incorrect) or 1 (correct) for each of the 12 single-choice questions, and 0 (incorrect) to 4 (absolutely correct) for the 6 other types of questions based on the number of correct choices. The total score of AIT is thus $1 \times 12 + 4 \times 6 = 36$, we calculated the average score per artifact, resulting in a score ranging from 0 to 6. Figure 15 presents an overview of the questionnaire data analysis results.

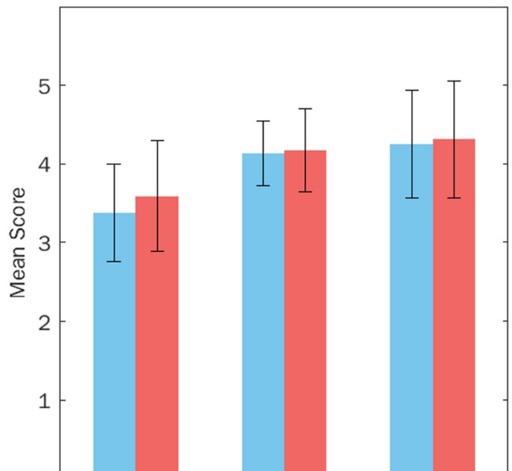
5.3.1. Intrinsic motivation

Mann-Whitney's U tests showed that there was a statistically significant difference in intrinsic motivation between CubeMuseum ($M = 4.95$, $SD = 1.00$) and CubeMuseum+ ($M = 5.80$, $SD = 0.83$) ($Z = -2.488$, $p = 0.012$). *H3a* is supported. Specifically, significant differences were reported in Interest/Enjoyment ($Z = -2.763$, $p = 0.005$) and Perceived Competence ($t(30) = -2.633$, $p = 0.013$). Although the differences in Perceived Choice ($Z = -1.705$, $p = 0.094$) and Pressure/Tension ($t(30) = 1.008$, $p = 0.321$) were insignificant, the scores showed a slight trend (see Figure 16).



	E	KL	ME	EC
CubeMuseum	3.43 (0.96)	4.04 (0.61)	3.70 (0.75)	3.05 (0.84)
CubeMuseum+	4.35 (0.86)	4.49 (0.57)	3.98 (0.88)	3.68 (0.98)

Figure 17. Means (with standard deviations) of the Engagement (E), Knowledge/Learning (KL), Meaningful Experiences (ME), and Emotional Connection (EC) in Museum Experience Experience (MES).



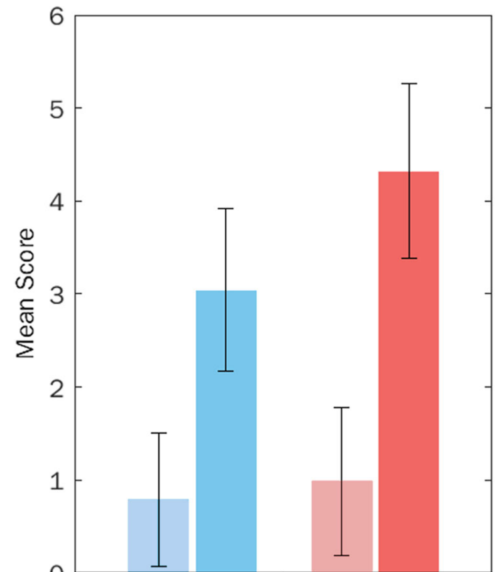
	GU	LC	QI
CubeMuseum	3.38 (0.62)	4.14 (0.41)	4.25 (0.68)
CubeMuseum+	3.59 (0.71)	4.18 (0.53)	4.31 (0.75)

Figure 18. Means (with standard deviations) of the General Usability (GU), Learnability and Control (LC), and Quality of Interaction with the Guide (QI) in Multimedia Guide Scale (MMGS).

5.3.2. Engagement

The analysis of MES showed that there was a statistically significant difference in museum experience between CubeMuseum ($M = 3.55$, $SD = 0.70$) and CubeMuseum+ ($M = 4.12$, $SD = 0.70$) ($Z = -2.227$, $p = 0.026$). *H3b* is supported in MES. Specifically, significant differences were reported in Engagement ($Z = -2.588$, $p = 0.010$) and Knowledge/Learning ($Z = -2.208$, $p = 0.029$). Although the differences in Meaningful Experiences ($Z = -0.928$, $p = 0.361$) and Emotional Connection ($t(30) = -1.943$, $p = 0.061$) were insignificant, the scores showed a slight trend (see Figure 17).

Figure 18 shows the analysis results of MMGS. There was no statistically significant difference in engagement with the multimedia guide between CubeMuseum (M = 3.92, SD = 0.41) and CubeMuseum+ ($M = 4.03$, $SD = 0.60$) ($Z = -.547$, $p = 0.590$). *H3b* is not supported in MMGS.



	CubeMuseum	CubeMuseum+
Pre-AIT	0.79 (0.72)	0.99 (0.79)
Post-AIT	3.04 (0.87)	4.32 (0.95)

Figure 19. Means (with standard deviations) of the overall AIT pretest and posttest results.

5.3.3. Learning Outcome

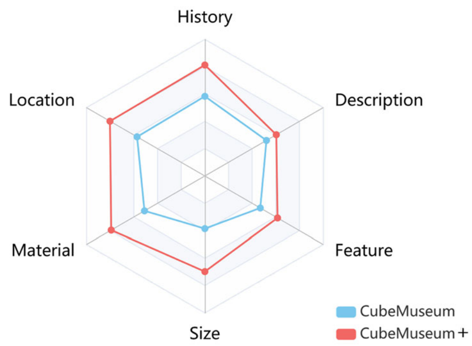
The analysis of the Artifact Information Test (AIT) showed no significant differences in the pretest ($t(30) = -.740$, $p = 0.465$), but significant differences in the posttest between CubeMuseum ($M = 3.04$, $SD = 0.87$) and CubeMuseum+ ($M = 4.32$, $SD = 0.94$) ($t(30) = -4.001$, $p < 0.001$). *H3c* is supported. Paired-samples *t*-tests showed that the AIT posttest scores were significantly higher than the AIT pretest scores ($p = 0.001$) (see Figure 19).

Further analysis on the six dimensions of AIT showed statistically significant differences in Location ($t(30) = -3.198$, $p = 0.003$), Material ($Z = -2.616$, $p = 0.010$), History ($t(30) = -2.588$, $p = 0.015$) and Size ($Z = -2.971$, $p = 0.003$) between CubeMuseum and CubeMuseum+. The differences in Feature ($t(30) = -1.679$, $p = 0.103$) and Description ($t(30) = -1.218$, $p = 0.233$) were insignificant, but showed a slight trend (see Figure 20).

Additionally, a Pearson correlation analysis was performed to determine the relationship between motivation, engagement, and learning outcome. The results indicated that there were strong positive correlations between motivation and learning outcome ($r = .475$, $p = 0.006$), and between motivation and engagement in museum experience ($r = .687$, $p < 0.001$). The correlation also showed there was statistically insignificant between motivation and engagement in the multimedia guide ($r = .284$, $p = 0.115$), and between learning outcome and engagement in museum experience ($r = .323$, $p = 0.071$) and multimedia guide ($r = .119$, $p = 0.517$).

5.3.4. Time spent with each interface

Unlike *Study 1*, we did not remind participants of the time used in this study. Welch's *t*-tests showed that there was a



History	Location	Material	Size	Feature	Description
3.50 (1.21)	3.44 (1.31)	3.06 (1.84)	2.31 (1.20)	2.81 (1.38)	3.13 (1.15)
4.88 (1.26)	4.81 (1.11)	4.75 (1.91)	4.19 (1.72)	3.63 (1.36)	3.69 (1.45)

Figure 20. Means (with standard deviations) of the AIT posttest results in six artifact dimensions.

statistically significant difference in time use between CubeMuseum ($M = 7.94$, $SD = 2.38$) and CubeMuseum+ ($M = 10.75$, $SD = 1.65$) ($t(30) = -3.883$, $p < 0.001$). It was expected because the optimized design has more functions to be explored.

5.3.5. Observations and interviews

Similar to *Study 1*, we adopted theme-based content analysis to analyze the observation notes and audio transcriptions of the interviews. We defined two high-level themes based on the structure of interview evaluations: learning effectiveness and playfulness. The sub-themes were identified by two researchers independently and agreed on afterwards. Details can be found in Appendix D. In addition, we asked participants to provide improvement suggestions for CubeMuseum AR, which were categorized based on the two high-level themes, and summarized in Appendix E. Furthermore, the implicated design of tangible AR interfaces in museum gifting are summarized in Appendix F, informing future designs to consider target group, intention of purchase, context of use, and cost.

5.4. Study 3 discussion

During the interview, participants provided their evaluations of CubeMuseum AR, with a specific focus on their learning and playing experience. Participants also shared their opinions on its use in museum gifting and provided some suggestions for future improvements. Our quantitative analysis has shown strong support for the effects of gamified TAR interface for learning. Still, we are interested to hear from users and to identify the underlying reasons from qualitative data.

5.4.1. Learning effectiveness

Similar to the findings in *Study 1*, *tangible manipulation* was found to be effective for learning. We observed that participants prefer rotating objects using the physical cube ($N = 15$) over touchscreen gestures ($N = 9$), indicating that tangible manipulations provide users with a more intuitive sense of control. Participants ($N = 2$) also highlighted in the interview that the replaceable cards add value to the tangible design. The gamification and visualization features we added to the optimized design contributed to the effectiveness of users' learning. Participants found the *timeline hall* helpful in the overall perception of artifact sizes ($N = 3$), the feel of cultural and social changes ($N = 2$), and also the recall of memory ($N = 1$). Similarly, the *map view* provided participants with an enhanced perception of museum locations and a recall of personal memory. Participants also favored *hotkeys* over information labels, for that they make it easier to focus on the details and allow quick navigation to the artifact features that they want to see. Some participants ($N = 3$) pointed out that the *audio guide* and background music made the exhibition more immersive.

When asked for suggestions for future improvements, the most frequently mentioned ones are about the use of *multimedia*. Some ($N = 4$) suggested the use of videos to present an intuitive presentation of the artifacts' stories. Others also mentioned the use of external links and high-resolution images, and proposed to minimize the use of texts. Some participants also identified the need for rich *guide* information, such as more historical stories ($N = 2$), HD images of features ($N = 2$), and information about discovered sites in the map view ($N = 1$). Participants ($N = 2$) hoped to see a complete guide tour so that they can choose if they want to view an exhibition in a suggested sequence. In addition to suggestions that addressed the need in *interface interactions*, such as to improve tangible controls and zoom functions, participants also seek for *social interactions* in their learning experience, both with other users and virtual characters. The need for social interactions was also highly mentioned for playfulness.

5.4.2. Playfulness

Most participants found that the learning and playing experience with CubeMuseum AR was interwoven with each other, and acknowledged that it was a playful learning experience. They expressed that *game features* made the application more engaging ($N = 2$). Due to the experimental setting in the lab, participants have limited resources to create artworks with the photo-taking function. Nevertheless, one mentioned that the AR *photo-taking* approach helps establish a personal connection with artifacts, which makes up for the regret of not being able to take pictures up close in the museum. Sharing artifact photos also provide the opportunity for social activities.

Social interaction was the most mentioned type of improvement suggestions for playfulness ($N = 5$). Participants proposed social functions such as artifact card exchanges, leaderboard rankings, social spaces for discussions, personal exhibition curation and sharing, etc. Participants also suggested the inclusion of more *gamification mechanisms* and *daily activities*, such as doing quizzes to gain points and exchange trophies, and to "bring artifacts to life" using subscription or daily push of artifact information. These seem to indicate participants' strong social needs, which have been identified in suggestions for both learning and playing. Considering that museum visiting and learning are essentially social activities, the support of social interactions is certainly worth investigating in the future.

5.4.3. Museum gifting

Similar to the findings in *Study 1*, participants found young people and children to be the ideal target group. Participants showed strong interest in the *hybrid design* and *digital affordances*, because it eliminates the constraints of time and space while providing vivid displays and rich digital content. Participants showed strong willingness to purchase CubeMuseum and build up their card collections during *physical museum visits* ($N = 8$). Participants see the use of CubeMuseum as an *onsite museum guide* ($N = 2$), and *outside the museum*, such as for classroom and at-home education and learning ($N = 2$). Participants indicated that CubeMuseum can be used as a travel guide system *before a museum visit* to find museums and artifact information ($N = 5$), and also *after museum visits* to help record past visits and artifact information, and customize theme-based exhibitions ($N = 2$). Based on the assumption of having a CubeMuseum, almost all participants in both Study 1 and Study 3 are willing to purchase more cards to enrich their CubeMuseum collection.

6. Overall discussion

We presented three studies that investigated the use of tangible AR interfaces for cultural heritage learning and museum gifting. Before we move on to the discussions of results and findings, we summarize our hypotheses testing results.

- **H1a** and **H1b** are supported. Users are more motivated and engaged when using TAR interfaces to learn about cultural heritage. Specifically, user motivation for CubeMuseum AR was significantly higher than using Leaflet; user engagement with CubeMuseum AR and Postcard AR was significantly greater than using Leaflet.
- **H1c** is not supported. Users did not achieve better learning outcomes when using (the initial) TAR interfaces to learn about cultural heritage.
- **H3a**, **H3b** and **H3c** are supported. Users are more motivated and engaged, and achieved better learning outcomes when using gamified TAR interfaces to learn about cultural heritage.

Overall, our studies showed positive effects of TAR interfaces for learning cultural heritage and great potential for it to be used for museum gifting. We next discuss our findings for the three research questions.

6.1. Tangible augmented reality for cultural heritage learning

How can TAR interfaces motivate, engage and support users in learning cultural heritage (*RQ1*)? First, the *digital affordance* of TAR is a great advantage of its use in cultural heritage learning. For example, users can access multimedia, get an overview of a collection and obtain a detailed view of an artifact using various visualization and interaction techniques, which are limited in a physical museum visit. Users showed high engagement in visual aspects of learning with TAR interfaces, such as artifact sizes and features. Second, users found the *tangible manipulations* provide an intuitive sense of control. Users prefer tangible interactions over touchscreen controls. Our finding is in line with the previous work showing that manipulable physical objects facilitate understanding and learning (O'Malley & Fraser, 2004). This is also why we considered the option of keeping 3D models in view when the cube is beyond the camera's range, but finally opted for the direct mapping between digital content and the physical cube. Third, the *hybrid design*. We found that user motivation correlates positively with the learning outcome. This indicates that while Leaflet showed good learning outcomes in our experimental setting, it is unlikely to help users' learning if they are not motivated to use it. On the other hand, TAR combines both digital and physical media. Interactive presentations of text descriptions in CubeMuseum + helped reduce users' memory load from reading long texts, and the print media is preferred by users for building up a personal collection. The combined use of digital and print media supports user motivation and engagement in cultural artifacts while maintaining learning efficiency.

We further investigated how effective can gamified TAR interfaces motivate, engage and support users in learning cultural heritage (*RQ3*). First, the effectiveness of several *gamification mechanisms* was assessed. Timeline hall, a map view, information hotkeys, AR photo-taking, and social sharing are successful gamification mechanisms to create a playful experience of cultural heritage. Participants also suggested other mechanisms that involve the social aspect, such as card exchanges, quizzes, leaderboard rankings, and social spaces. These will motivate users to play, compete and share with each other, and engage users in learning about cultural heritage. Future work can explore gamification mechanisms that were found helpful to engage visitors in onsite visits, such as treasure hunts (Cesário, 2019; Goodlander, 2009), and combine them to create a hybrid and coherent museum experience. Second, users expect to have *personalized experiences* with TAR interfaces. This was reported by participants in the interview, hoping to store artifact information, record past visits, build collections of cards, etc. Examples also include a personal virtual museum space, where they could curate an exhibition to showcase their collections, visit others' collections, and invite others to come and visit. Previous work also identified users' needs in collecting and sharing memories in museums (Kostoska et al., 2013). We see participants' needs in not only generating personal meaning-making of cultural heritage but more importantly the sharing of understandings and interpretations through the construction and sharing of personalized experiences. Third, *social interactions* contribute to the playfulness of cultural heritage experience. Both gamification and personalization involve activities that are social. This is because learning is a social activity, and museum visiting is also a social experience that derives from their physical interactions with artifacts (Henderson & Atencio, 2007). Users' evaluations and suggestions have largely addressed their social needs. Therefore, supporting user engagement in social interactions is the next important step for users to be able to not only play alone but play together with others.

To summarize, TAR interfaces could motivate, engage, and support users in learning cultural heritage with its rich digital affordances, intuitive tangible control, and hybrid design. The game mechanisms, personalized experiences, and social interactions supported in the CubeMuseum + further improved user motivation, engagement, and learning outcomes. We reflected on the experiments and summarized several lessons learned for future work. First, users' learning efficiency is better if an *overview of artifacts* is supported. The initial CubeMuseum design does not support an overview as Postcard AR and Leaflet do. The optimized design supports overviews in the timeline hall, map view, and favorite collections, which helped with users' learning effectiveness. Second, the proposed TAR interfaces could be used for *guide tours*. With the mental model transferred from the physical museum visits, some users prefer to take a guided tour in a suggested sequence. Providing free control of embodied guides such as virtual avatars (Li et al., 2019) is an appropriate method for virtual exhibitions. Third, *interaction with other users* is an important motivation factor in the learning process, and a way to support users in continuous learning. Previous work showed that AR can be used to support spectator experience and enrich the social contexts of museum experience (Li et al., 2022). The expected involvement of other users, virtual characters, and sharing activities in user feedback confirmed the need to support social interactions. Forth, future work should improve user perception of the actual size of museum artifacts. Although the timeline hall view in the optimized design provided users with a relative comparison of artifact sizes, some participants still felt hard to perceive the actual size of the artifacts. The perception of size with mobile AR devices seems to remain a challenge. Simulating the museum setting, or displaying an artifact on a ground plane to show its relative size to real-world objects are perhaps good solutions to support users' perception of size.

6.2. Tangible augmented reality for museum gifting

How do users perceive the use of TAR interfaces for museum gifting (*RQ2*)? We interviewed experts and young people and surveyed the general public to understand this research question. The results showed several great potentials of TAR interfaces (CubeMuseum AR and Postcard AR) in museum gifting. We summarize the following lessons to better implement TAR interfaces for museum gifting. These provide insights for museums to convey cultural values through tangible creations.

6.2.1. Acceptance

Young people are more familiar with 3D graphics and AR technologies, thus more acceptable to TAR interfaces, and more likely to purchase AR tangibles. Users found AR to be acceptable to young people and children, thus are more willing to purchase AR tangibles as gifts to users in this age group.

6.2.2. Purchase intention

Digital design, physical material, and cost are important considerations for users' decisions in gifting. Specifically for digital design, users like novel interfaces that are playful, customizable, of rich digital content, and easy to access. As indicated in the previous work (Back et al., 2018), playfulness is an important part of the gifting experience. In the meantime, the physical product should be aesthetically appealing and ideally of practical use. Overall, users like products that can attach personal meanings and are of reasonable prices (∼200 RMB or ∼30 USD). The total cost for the optimized physical design (acrylic cube with card slots, wooden base, and cards) is less than 5 USD, which is cost-effective, feasible for mass production, and has a large room for profiting. It is also possible to use other materials to cater to a more high-end gift choice.

6.2.3. Customization

Being able to customize is important for the gifting experience. Customization can be allowed in physical or digital form. CubeMuseum AR supports users in building a customized collection by selecting and arranging cards of cultural artifacts. The optimized design also supports the customization of digital content through photo-taking and social sharing. User-generated content reflects visitors' personal interpretation, which is an essential part of learning in museums (Falk & Dierking, 2000). Attaching personal meanings in customization also adds sentimental values to a gift.

6.2.4. Collection and expansibility

Participants expressed strong purchase intentions for CubeMuseum AR cards, indicating that the item collection mechanism can promote users' continuous interest in cultural heritage. The design supports user motivation and encourages users to continue their explorations and learning of cultural artifacts.

6.2.5. Digital exhibitions and physical museum experience

TAR interfaces are complements to physical museum visits, not replacements. In fact, digital exhibitions in the form of tangibles, online museums, and virtual museums can never replace physical museum exhibitions. Digital curation should adapt to users' mental models of physical visits, such as keeping the information labels and providing guided tours. TAR interfaces such as CubeMuseum AR can help attract and motivate users to visit physical museums for the first time (and revisit them) to see the artifacts onsite. This is a great value as a museum gift.

6.3. Limitations and future work

This research has some limitations and room for future work. We start with a discussion of threats to the validity of our study (Wohlin et al., 2012). First, the current evaluations were primarily performed by Chinese young people. This is a threat to the external validity. Although our second study indicated that young people are a typical target user group for AR, interviews with experts and participants indicated that children and teenagers are also a potential target group. Unfortunately, we have limited data about these age groups. Some findings, such as the interview opinions, should be interpreted carefully outside the eastern country context. Second, learning in museums is a long-term and informal process, and is largely influenced by the physical and sociocultural contexts. The duration and contexts of learning are two threats to the internal validity of this experiment. Future research can explore the impact of tangible AR interfaces on users' long-term learning, and learning within the museum space. Third, the current design has limited support for social interaction, which seems to be essential for learning motivation, playfulness, and continuous learning outcomes. Future work should address the social aspects of TAR, such as collaborative behavior using mobile devices Chen et al. (2020), to support the learning of cultural heritage. Aside from learning motivation and engagement, participants' emotions are an important aspect of the evaluation to understand their learning experience. Fourth, our current designs show artifact information prepared by us. With the fast-developing mobile scanning technologies, it is possible in the future for users to take pictures of museum artifacts, create 3D photogrammetry models, and curate their own digital exhibitions. Finally, our intended design of CubeMuseum AR and Postcard AR was for museum takeaway experiences. It exceeded our expectations that participants (both museum experts and young people) found them applicable in more scenarios. For example, three experts are willing to adopt them in their onsite education workshops; participants also see its potential use as a travel guide, a memoir, a collection book, and even a daily app. There are several great potentials to explore different use scenarios and to provide more targeted designs for better support of cultural heritage learning and gifting experience.

7. Conclusion

In this paper, we presented three studies that investigated the effects of tangible augmented reality (TAR) interfaces, especially gamified TAR interfaces for cultural heritage learning and museum gifting. We first presented a study based on three interaction interfaces for cultural artifacts: CubeMuseum AR, Postcard AR and Leaflet. We explored their effects on users' intrinsic motivation, engagement, and learning outcome. Our findings indicated that users are more motivated and engaged in learning with TAR interfaces. The difference in learning outcome was insignificant. Our results also confirmed the strong positive correlation between motivation and learning outcome. The qualitative analysis of observations and interviews showed that Postcard AR provides necessary tangible interactions with 3D graphics and maintains the learning advantage of paper reading and overview; CubeMuseum AR provides the greatest sense of control via tangible interactions, which largely stimulates users' interest in learning of cultural artifacts. To enhance learning performance with TAR interfaces, we explored ways to optimize CubeMuseum AR through in-depth interviews with cultural heritage experts and an online survey with the public. Based on the findings, we improved both the physical and digital design of CubeMuseum AR. To be specific, we reduced its weight and added a Chinese-style wooden base to improve its ornamental look. We increased the playfulness in its digital design by combining animations, favorites, information hotkeys, timeline hall, a map view, photo-taking, and social sharing features. A between-subjects user study results indicated that the optimized CubeMuseum AR significantly improves user motivation, engagement, and learning outcomes in cultural heritage experience. Analysis of the observations and interviews showed that the gamified CubeMuseum AR supports users' learning with its playful features, effective visualizations, and the support for personalized experiences and social interactions.

In short, our study demonstrates the feasibility and practical value of TAR interfaces combining gamification mechanisms for cultural heritage learning and museum gifting. Our statistical findings on motivation and engagement are generalizable for learning and education. Within the HCI community, the results provide insights and facilitate discussion on how ubiquitous devices and interactive systems that are inexpensive to build and work well with existing widely-available technology can be used to enhance museum learning experiences, promoting a wider application of interactive technologies to the cultural and creative industries. The interviews with domain experts add significant value to the HCI community with a specific interest in cultural heritage, and more specifically Chinese cultural heritage. The discussion of design implications and future work provides insights for museum researchers and practitioners in designing novel interfaces and physical manipulatives for learning and gifting, and shows implications for technology-enhanced learning.

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Appendix A. Overview of 12 cultural artifacts

#	Name	Picture	Size	Time period	Museum	Material
1	*The Bronze Mask with Protruding Pupils*		Height: 66 cm Width: 138 cm	Shang 1600–1046 B.C.	Sanxingdui Museum	Bronze
2	*Ke Clan Bo*		Height: 63 cm	Western Zhou 1046–771 B.C.	Tianjin Museum	Bronze
3	*Kneeling Archer*		Height: 182 cm Width: 64 cm	Qin 221–207 B.C.	Qin Terra-Cotta Warriors Museum	Ceramics
4	*Tri-colored Camel*		Height: 87 cm	Tang 618–907 A.D.	Nanjing Museum	Ceramics
5	*Pottery Figure of a Standing Lady*		Height: 138 cm Width: 26.6 cm	Tang 618–907 A.D.	National Palace Museum, Taipei	Ceramics
6	*Marble Statue of Sakyamuni*		Width: 40 cm	Liao 907–1125 A.D.	The Capital Museum	Marble
7	*Gold-plated Bronze Bull Statue*		Height: 45 cm Width: 38 cm	Western Xia 1038–1227 A.D.	Ningxia Museum	Bronze
8	*Vajrasattva Bronze Statue*		Height: 21.4 cm Width: 115 cm Depth: 11 cm	Ming 1038–1227 A.D.	Sichuan Museum	Bronze
9	*Blue-and-White Vase with Peons Scrolls Design*		Height: 44 cm	Yuan 1271–1368 A.D.	Nanjing Museum	Ceramics
10	*Eight Corners Case*		Height: 31 cm Width: 27.3 cm	Ming 1368–1644 A.D.	Zhejiang Museum	Lacquerware
11	*Figure of an Assistant to the Judge of Hell*		Height: 148 cm Width: 36 cm Depth: 20 cm	Ming 1522–1620 A.D.	The British Museum	Ceramics
12	*Chinese Imari Covered Bowl with Floral Sprays*		Height: 24.3 cm Width: 19.5 cm	Qing 1622–1722 A.D.	Palace Museum	Ceramics

Appendix B. Summary of user evaluations of three interaction interfaces

Theme	Interaction interface	Attitude	Description	Participant ID
Effectiveness	CubeMuseum	Pros (6)	Easy to learn and effective to use.	P2, P10
			Free arrangement of cards.	P2, P21, P19
			Prefer paperless reading.	P13
		Cons (3)	Size information and text descriptions cannot be displayed at the same time.	P3, P13, P17
	Postcard	Pros (8)	Paper reading is more effective (e.g. to take notes and highlight).	P1, P2, P9, P15, P18
			Free arrangement of cards and comphrehensive overview.	P2, P21, P19
	Leaflet	Pros (9)	Paper reading is more effective (e.g. to take notes and highlight).	P1, P2, P9, P15, P18
			Prefer to learn and memorize with paper-based media.	P9, P18
			Good overview with different artifacts shown together.	P9, P19
Motivation	CubeMuseum	Pros (9)	Novel and attractive interface.	P6, P7, P9, P11
			Use of AR can stimulate interest in artifacts.	P1, P2, P18
			Intuitive interactions with the 3D models and easy to learn.	P2, P18
	Postcard	Pros (5)	Use of AR can stimulate interest in artifacts.	P1, P2, P18
			Intuitive interactions with the 3D models and easy to learn.	P2, P18
	Leaflet	Pros (2)	A classic way of learning, easier and more acceptable than technology-based learning.	P9, P21
		Cons (9)	Too ordinary to stimulate interest.	P3, P6, P7, P8, P11, P13, P19, P21, P22
Tangible manipulation	CubeMuseum	Pros (7)	Manipulating the cube provides an increased sense of control.	P8, P11, P22
			Replaceable cards allow for more possibilities.	P4, P6, P7, P13
	Postcard	Cons (3)	Scaled up models may block the text descriptions in view.	P1, P14, P15
Presence	CubeMuseum	Pros (8)	3D models increase presence with artifacts.	P2, P3, P4, P9, P20, P23
			Scaling provides more details about the artifact.	P11
			The option to see the artifact itself without text descriptions.	P22
	Postcard	Pros (8)	3D models increase presence with artifacts.	P2, P3, P4, P9, P20, P23
			Viewing 3D models and text descriptions together can reinforce memory.	P15, P18
	Leaflet	Pros (1)	No interaction needed, so good to focus on memorizing.	P14
		Cons (2)	Static images are not as vivid as 3D models.	P6, P22

Appendix C. Summary of important factors of users' choices in museum gifting

Theme	Interaction interfaces	Attitude	Description	Participant ID
Target group	CubeMuseum	Pros (5)	Good for young people who like new things.	P1, P2, P9, P16, P23
		Cons (1)	Probably not easy to be accepted by the elderly.	P1
	Postcard	Pros (4)	A good choice for friends who like collecting postcards.	P5, P6, P21, P24
	Leaflet	Cons (6)	Too boring for young people.	P1, P3, P6, P16, P22, P19
Digital design	CubeMuseum	Pros (6)	Novel interaction with the cube and the cards.	P11, P9, P23
			3D models can be viewed at different angles by rotating the cube.	P1, P5, P12
		Cons (4)	Unable to perceive the true size of an artifact.	P1, P3, P8
			Brief information on each side of the cube, can't see details without the app.	P19
	Postcard	Pros (1)	Can write words and add personal meanings to a gift.	P21
		Cons (10)	Unable to perceive the true size of an artifact.	P1, P3, P8, P15, P21
			Scaled up models may block the text descriptions in view.	P1, P14, P15
			Too much text information for a postcard.	P19
	Leaflet	Cons (7)	Leaflet is too ordinary to be a gift.	P3, P6, P8, P11, P13, P21
			Inconvenient to flip.	P1
Physical material	CubeMuseum	Cons (9)	Too heavy.	P1, P2, P6, P8, P11
			Inconvenient to carry.	P1, P11, P21
			Edges are too sharp.	P3
	Postcard	Cons (1)	The paper is a bit reflective.	P23
	Leaflet	Cons (1)	The paper is a bit reflective.	P23
Cost	CubeMuseum	Pros (1)	Will buy if the price is reasonable.	P15
	Postcard	Pros (1)	Will buy if the price is reasonable.	P15
	Leaflet	Cons (2)	Useless.	P3, P11

Appendix D. Summary of user evaluations of CubeMuseum AR for learning

Theme	Feature	Description	PID
Learning effectiveness	Tangible manipulation (5)	Learning by manipulating the physical object and controlling the virtual artifacts is a great experience.	P1, P20, P27
		The replaceable card design is cool and unique.	P10, P32
	Timeline hall (6)	The timeline hall helped me have an overall perception of the artifact size.	P6, P10, P17
		The historical timeline clearly indicates the dynasty to which artifact belongs, and I can feel the cultural and social changes.	P3, P7
		Some visualization functions like timelines and artifacts are easy to recall.	P12
	Map view (5)	It is so clear to see the museum location of cultural artifacts with map view.	P2, P3
		It is intuitive to see the location of the artifacts by combining geographical knowledge.	P9, P25
		The map covers some museums, and you may remember it from your journey.	P27
	3D model (4)	The artifact can be observed from multiple angles.	P16, P26, P31
		3D model is the most attractive part, which arouses curiosity and stimulates the subsequent exploration.	P4
	Hotkey (3)	Hotkeys make it easier to focus on the details.	P3, P23
		Hotkeys allow me to quickly locate the artifact features that I want to see.	P1
	Audio guide (3)	Audio guide and background music made the exhibition more immersive.	P1, P3, P27
	Info label (1)	Artifact information labels provide a comprehensive intro.	P3
Playfulness	Gamification (2)	The game functions make the app more engaging.	P2, P11
	Photo-taking (1)	Taking photos of artifact in this application has brought me closer to them.	P28
	Social sharing (1)	Social sharing can make more people interested in using the CubeMuseum.	P25

Appendix E. Summary of user suggestions for CubeMuseum AR

Theme	Feature	Description	PID
Learning effectiveness	Multimedia (6)	Videos can give an intuitive presentation of the artifacts' stories.	P2, P20, P23, P26
		Artifact map is useful for tour planning. Could add links to use other navigation applications.	P4
		Reading text usually does not have the patience to memorize, minimize the text as much as possible.	P8
	Guide (6)	Add more historical stories related to artifacts.	P3, P16
		Provide partial HD image for highlighted features in hotkey mode.	P7, P13
		Demostrate the discovered sites of aritfacts in the map.	P26
		Provide users with a complete guide tour. Users can freely choose if they want to view the exhibition in sequence.	P29
	Interaction (2)	Increase the tangible interaction by embedding virtual buttons on the physical cube.	P2
		Support zoom in and zoom out functions in the map.	P25
	Social interaction (3)	Have more share content and more interactions with other users.	P3, P27
		Set up a virtual character that we can interact with.	P2
Playfulness	Social interaction (5)	Add more entertainment and social functions for adult users, such as changing cards with other users and leaderboard.	P4, P9, P23
		Add a social space for people to discuss cultural artifacts.	P9
		Add a personal 3D virtual museum. It can be an exhibition curated by me, so that others can visit my exhibitions.	P25
	Gamification (1)	Add game quiz mechanisms, such as exchanging a trophy using gaining points.	P12
	Daily activity (3)	Add a subscription push or daily cultural material push, 'bring artifacts to life'.	P16, P19
		Add daily tasks to increase user engagement.	P6

Appendix F. Summary of user evaluations of CubeMuseum AR for museum gifting

	Theme	Description	PID
Purchase intention	Target group	Children are interested in exploring things like that.	P9
		Will buy them for people who haven't seen these artifacts in museums.	P16
		People who don't like to go out would prefer watching digital exhibitions in this app.	P23
		Young people are receptive to new technology and like interesting things.	P27
	Novelty (2)	It is a very novel gift for teenagers.	P27
		AR souvenir is more innovative than traditional ones.	P26
	Hybrid design (6)	I like this type of souvenir with both ornamental and practical value.	P25, P26
		The artifact cards are of meaningful values with the hybrid design. I might go to museums to collect them.	P22
		Using the hybrid gift requires to download an APP. Web-based or WeChat mini programs will be more acceptable.	P10, P20, P24
	Digital affordance (5)	Convenient to observe artifacts anytime and anywhere.	P17, P23
		Virtual objects are better than real objects because of the clear and complete view.	P2
		More useful than traditional museum souvenirs.	P3
		The artifacts are so vivid that makes me want to buy this.	P21
	Physical museum visits (8)	These virtual artifacts motivate me to go to real museums and see the real objects.	P6, P15, P17, P26
		Will go to the museums if they have this kind of novel gifts with cultural characteristics.	P4, P5, P6
		I like to buy digital museum souvenirs for collection, but these can't replace real artifacts.	P22
Context of use	Onsite guide (2)	It can be a great guide for viewing artifacts in the museum.	P16, P23
	Outside museums (2)	It can be used for classroom education and home education.	P16, P30
	Before visits (5)	It can be used as a travel guide to find museums and corresponding artifacts.	P2, P3, P7, P17, P25
	After visits (2)	It is a good carrier of artifact information, which can be used to record the track of travels.	P9
		Users can customize theme-based exhibitions with the cube to have a personal experience.	P16
	Anytime (1)	It provides a convenient way to get 3D views and relevant information whenever you want to see the artifacts.	P27
		It provides a convenient way to get 3D views and relevant information whenever you want to see the artifacts.	P27
	Cost	Will buy if the price is reasonable.	P1, P3, P12, P15, P23, P29
		Paper cards are usually cheap, so people are willing to continue to buy artifact cards to build up their collection.	P5, P7, P10, P18
		I expect the price of the CubeMuseum to be slightly lower than the 3D printed artifact replicas.	P20

Appendix G. Summary of Cronbach's alpha reliability results

	Questionnaire	Subscale	CA
Study 1	Intrinsic Motivation Inventory (IMI)	Interest/Enjoyment (IE)	0.76
		Pressure/Tension (PT)	0.81
		Perceived Choice (PCH)	0.80
		Perceived Competence (PCO)	0.87
	User Engagement Scale (UES)	Focus Attention (FA)	−0.35
		Perceived Usability (PU)	0.88
		Aesthetics (AE)	−0.24
		Reward (RE)	−0.27
Study 3	Intrinsic Motivation Inventory (IMI)	Interest/Enjoyment (IE)	0.80
		Pressure/Tension (PT)	0.9
		Perceived Choice (PCH)	0.81
		Perceived Competence (PCO)	0.81
	Museum Engagement Scale (MES)	Engagement (E)	0.79
		Emotional Connection (EC)	0.80
		Knowledge/Learning (KL)	0.80
		Meaningful Experience (ME)	0.81
	Museum Multimedia Guide Scale (MMGS)	General Usability (GU)	0.82
		Learnability and Control (LC)	0.83
		Quality of Interaction (QI)	0.83