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Design and Evaluation of a Distance-Driven User Interface for Asynchronous Collaborative Exhibit Browsing in an Augmented Reality Museum

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ABSTRACT Augmented reality museums allow visitors to jointly view and interact with exhibits. However, real-time exhibit browsing does not accommodate latecomers to museums and offers limited support to temporally separated visitors. To stimulate asynchronous exhibit browsing, we developed a distance-driven user interface that divided the augmented reality exhibit-egocentric space into four distance ranges, each having a set of social networking features and different privileges for exhibit viewing and interaction. The user interface enables asynchronous exhibit browsing for visitors participating at different times. We conducted empirical studies to evaluate how the user interface affected visitors’ collaborative exhibit browsing in terms of perceived usability and learning gains. The results show that the perceived usability of the user interface is consistently high across all distance ranges. The user interface stimulates collaborative exhibit browsing with significant improvements in learning efficiency and learning attention durations, although learning satisfaction showed no difference across the participants. Implications for how the distance-driven user interface can be generalised for other interactive applications are discussed.

INDEX TERMS Distance-driven user interface; asynchronous collaboration; collaborative exhibit browsing; augmented reality museum

I. INTRODUCTION

We have witnessed rapid advancements in augmented reality (AR) in the cultural heritage context in recent decades. Thus far, conventional museums have opened digital doors to visitors with diversified exhibits that are equipped with interactive technologies [1]. With devices such as HoloLens [2] and AR-enabled mobile phones [3], visitors can jointly view and interact with physical exhibits and virtual information without interfering with other visitors. For example, visitors can simultaneously rotate a virtual copy of an exhibit without interfering others and work with other visitors without compromising the individual exhibit browsing experience. Multiuser collaborative exhibit browsing has a positive effect on user engagement as it improves users’ interaction motivation, work efficiency, and productivity [4] and develops supportive social relationships among users [5].

However, synchronous exhibit browsing does not accommodate latecomers to the museum and offers limited support for temporally separated visitors. Additionally, synchronous collaborative browsing may suffer weak responsibility issues [6], which limits visitors to share their feelings and learning proactively during exhibit browsing. Several virtual museum applications, such as the research of [7, 8], have been developed for multiuser exhibit browsing. These applications can run multiple instances of virtual and/or augmented reality museums in parallel with access to the exhibits at any time and from anywhere. However, few of these applications have considered the exhibit egocentric space to stimulate collaborative exhibit browsing across visitors who stand at different distances to the exhibit and visit the exhibits at different times in the AR museums.

The user-exhibit distance is an effective communication medium and interaction modality in proxemic interaction [4]. It conveys useful information such as user interests, engagement, and interactivity [9]. In public museum space, as visitors continuously move during space navigation and exhibit browsing, the distance can be qualified as a dynamic indicator of user communication status and/or intention, and it is an efficient measurement of multiple user behaviour movements and interaction purposes [10, 11]. As a proven interaction modality for multiuser interaction, the user-exhibit distance can benefit visitors in collaborative exhibit browsing.

To examine stimulating asynchronous collaborative exhibit browsing with user-exhibit distance in an augmented reality museum, we present a distance-driven user interface. The interface divides the exhibit egocentric space into four distance ranges, each associated with a set of interaction privileges in terms of exhibiting information browsing and sharing. Furthermore, we conducted empirical studies to evaluate how the proposed user interface influenced the participants in terms of perceived usability and learning gains.

The main contributions of the paper are twofold. First, we present the design of a distance-driven user interface which divides the exhibit egocentric space into four distance ranges of information viewing and exhibits interaction to leverage asynchronous multiuser collaboration at various distances. The user interface integrates conventional interactive space models with social network features in the context of an augmented reality museum, which is novel over existing proxemic interaction space model-based user interfaces. Second, the paper supplies new understandings of how the distance-driven user interface affects asynchronous collaborative exhibit browsing with respect to the perceived usability and learning gains, together with implications for how the model may be implemented for generalising applications.

The remainder of the paper is structured as follows. Section 2 reviews related work on augmented reality museums, proxemic interactions and collaboration in augmented reality museums. Section 3 describes methodological details of the design and evaluation of the distance-driven user interface. Section 4 presents the study data analysis and results. Section 5 discusses the study findings and implications for how the model can help to generalise applications. Section 6 concludes the study's findings.

II. RELATED WORK

A. Augmented reality museum

A museum is an institution of comprehensive collection, display, education, and research, providing the public with a platform storing and sharing knowledge of art and antiques [12]. The development of the Internet and multimedia technology spawned the concept of digital museums [13] or intelligent museums [14]. Given the rapid advancements of these technologies, virtual museums are emerging as a new mode of participation, interaction, exploration, and experience, and attract more visitors with finer museum experiences [15].

Early studies considered augmented reality to be a useful tool for enhancing visitors' overall experience [15]. For example, AR maximises information delivery to visitors over physical museum environments without compromising museum exhibits or disrupting visitor viewing [16]. Meekaew et al. [17] found that students who used mobile-game-based learning integrated with augmented reality had better understanding and stronger learning motivation than those using only game-based learning. Lin et al. [18] reported that integrative multimodal representations in augmented reality museums improved user interaction engagement and effectiveness in terms of situated cognition and learning.

To access augmented reality museums, there are two types of mainstream devices: wearable headsets (e.g. Microsoft Hololens [2]) and mobile phones. Spatial-display-based augmented reality systems also exist in some augmented reality applications, but they are few in number [8]. Headset devices support multimodal interactions (e.g. eye gaze, in-air hand gestures, and body motion) with physical artefacts [2]. However, due to their low cost and ease of use, mobile-phone-based AR devices [3] are widely adopted by consumers. Other mobile-phone-based AR headsets, e.g. Holokit [19] and Aryzon [20], developed mobile-phone-based cardboard headsets and achieved high usability in practical use. However, how such devices can effectively stimulate asynchronous collaborative exhibit browsing in AR museums is not of significant concern.

Early research placed a strong focus on the interaction between users, exhibits, and environments in AR museums. These studies explored AR museum applications and their exhibition interactivity [21], spatial navigation [22], interactive exhibition environment construction, and scene exploration [23]. For example, Barbier et al. [21] implemented an augmented reality annotation tool to annotate 3D models, and Rabbaa et al. [22] designed MRsive to simplify navigation cognitive efforts and boost visitor engagement with museum artefacts through multisensory interaction.

Multiuser collaboration of exhibit interaction was less examined in early studies. Collaborative interaction in AR museums can enhance the visitors' overall experience [7], and early studies attempted different methods of collaboration, e.g. the universal scent blackbox used smell as an evocative interface to stimulate users to create and share olfactory experiences with others [24]. Following this direction, several collaborative AR museum applications were developed [7, 8], although how to effectively improve the collaborative interaction of the AR museum with a proxemic interface was underestimated.

B. Asynchronous Collaboration in Augmented Reality

Collaborative interaction refers to users' cooperative responses to accomplishing shared goals [6, 25]. It positively affects users' working efficiency and deepens user engagement. One application of augmented reality is to develop new types of collaborative interfaces and technologies [26]. However, there are several factors hindering collaborative AR museum applications: device cost, system usability, and interaction modes. To address these issues, early research adopted different interaction modalities, e.g. eye gaze [27], hand gestures [28], environment [29], and selected objects [27] to seamlessly integrate digital information in virtual and physical space. These studies found that sharing eye gazes could help users shape the sense of collaboration, and that sharing data on users' interests was useful in enhancing users' awareness of collaboration [29].

Collaboration is part of many augmented reality applications in innovative design [30], entertainment [31], education [32], and cultural heritage [23]. Of these applications, learning and education account for a large proportion [32]. Georgiou et al. [33] found that students were positively engaged at different immersive levels, e.g. content, motivation, emotion, and engagement in location-based augmented reality science activity. Similar effects were validated in another study [34], which showed that collaboration stimulated augmented reality content sharing. User collaboration was affected by several factors such as locations [35], synchronization [36], and user abilities [37]. In addition, multidevice interaction provided new possibilities for collaboration in the AR context [7]. Some pioneering works developed floor-based user interfaces to support multiple users to explore the spatial augmenter reality environment with monoscopic and stereoscopic projections [8]. The user interface was effective in guiding different users to exhibits, whereas it distracted the users from intended exhibit viewing and learning, as users in the same physical museum space had individual interests and interaction abilities.

Early research in augmented reality collaboration focused on synchronous communication, which points to sharing information or feedback and interacting in real time between multiple users to achieve a common goal [36]. Ben Rajeb et al. [30] presented a remote synchronous collaborative graphical tool to enable the remote sharing of documents and annotations in real time. A mobile AR game [31] provided players engaging in synchronous and collaborative interactions with other players in a shared, real-time augmented environment. Müller et al. [38] investigated virtual work objects as references integrated into the physical environment to guide collaborators to maintain real-time attention.

Synchronous collaboration cannot cover the latecomers and has limited support to temporally separated participants. To implement asynchronous collaboration in augmented reality museums, there are difficulties to overcome [39]. First, visitors can join the collaboration at any time without interrupting ongoing collaboration interactions. For example, augmented book [34] allowed AR content incorporated in a book to be shared and explored by other users joining at any time. Second, the task of asynchronous collaboration needs to be open-ended during a long time span, during which latecomers may interact with the early visitors' information, e.g. sharing user comments on a social live video streaming platform requires all comment information to be stored in a system over an extended time duration [40].

C. Distance-driven user interface

The physical spatial distance between humans and humans was regarded as an invisible dimension of communication by Hall in the early 1960s [41]. Following that, studies showed that the user-display distance served the same role in proxemic interaction with large displays and immersive environments [4, 42], i.e. when a user approaches a kiosk of tourist guide, s/he indicates explicit interests to the target through distance changes. As a proven interaction modality, distance is incorporated for the geometric rendering of user interface displays in augmented reality applications [2]. Unlike event-driven modalities such as hand gestures [43], distance is an implicit interaction modality that continuously reflects users' movement behaviours [44]. Early research showed that distance was an influential factor of perceived usability in large display interactions, although it had limited input channels [43]. Therefore, the distance suitably serves as the modality in augmented reality interaction.

By distance, the early research mostly refers to the physical space between user and artefacts of interacting, and similar concepts of the distance include human proxemics [45], human-object distance [9], human-robot proxemics [46], human-interface distance [11], and human-virtual distance [47]. These studies explored user-centred interaction techniques and user interfaces related to physical or virtual distance. Gao et al. [47] used egocentric distance-based item sizing in a virtual environment, which enlarged item sizes according to the distance, to improve the visual experience and secure item selection performance. Pederson and Surie [9] proposed an egocentric interaction model based on human perceptual characteristics to enable activity-aware wearable computing.

Users perceive distance differently in physical and virtual reality [48]. Compared with physical reality, early research highlighted that the user-artefact distance used to be underestimated in virtual environments [49]. The user-object distance in the physical world often refers to the horizontal distance between the observer and the target artefact, which are both located on a round plane [48]. Kelly et al. [49] complemented that after visual preview of the real environment, users perceived the distance in a replica virtual environment with higher accuracy. Fewer investigations have been conducted on the role of perceived distance in collaborative interaction, where physical and virtual distance coexist.

Intangible distance was also considered in socialisation scenarios. This enables users to connect and collaborate closely [50]. For example, short spatial distance raised the intimacy of interactive relationships between users [45], and the distance played an effective role in relation prediction of social networks [51]. Spatial distance is calculated as the difference of geographic locations of users, and the location-based social networks were extended to augmented reality applications, i.e. users published augmented reality content in one location and interacted with this content in other locations [50]. In this application, the calculation of users' real-time locations was based on GPS and the relative moving distances positioned by AR tracking.

D. Lessons learned and hypothesis development

The preceding review accentuates the gap of multiuser asynchronous collaboration in exhibit browsing. It summarises existing research in and applications of augmented reality museums, collaborative interactions, and distance-driven interactions. Additionally, it highlights factors such as device cost and virtual distance measurement, which hinder asynchronous collaborative interaction in augmented reality museums. The review indicates the feasibility of user-artefact/display distances as an effective communication medium of multiuser interaction and the possibility of using social networking features as an integral form of distance. Therefore, we are motivated to develop a distance-driven user interface to stimulate asynchronous collaborative exhibit browsing in augmented reality museums.

The user interface integrated two main features to fulfil the requirements for asynchronous collaboration of exhibit browsing. We developed the user-exhibit distance model to allow users to join ongoing collaborative exhibit browsing. Additionally, we introduced social networking functions (e.g., thumbs-up LIKE) as an open-ended task. According to the understanding of the two functions in early research, we proposed the null hypotheses of the study as follows:

H1: The distance-driven user interface with egocentric distance ranges will not stimulate participants' asynchronous collaborative exhibit browsing.

H2: The distance-driven user interface with social networking features will not enhance participants' learning gains during asynchronous collaborative exhibit browsing.

III. METHODS

The objectives of the study are to investigate how the distance-driven user interface stimulates visitors' asynchronous collaboration to exhibit browsing. The independent variables are the distance-driven user interface (the primary independent variable is user-exhibit distance, and the secondary independent variable is privileges of exhibit browsing), and the dependent variables are the participants who collaboratively exhibit browsing in terms of perceived usability and learning gains. These are measured with multimodal methods. Below, we describe details about the design and evaluation of the distance-driven user interface.

A. Design of distance-driven user interface

1) DISTANCE RANGES

The core of the distance-driven user interface is the user-exhibit distance model. It divides the exhibit egocentric space into four ranges according to users' interaction purposes and

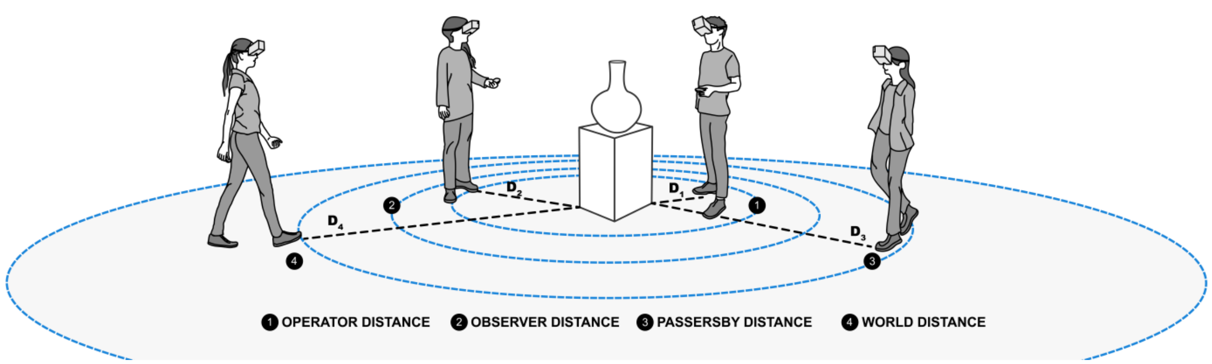

FIGURE 1. Exhibit egocentric distance ranges

abilities (FIGURE 1). The division was based on the user egocentric interaction model in the research of [9], which described the user's front space as four respective distances: operation distance, observation distance, identification distance, and nonnoticing distance. The detailed ranges and related reasons for the four distances are described as follows:

(1) Operator distance, ranging from 0 to 0.6 m from the exhibit. This distance belongs to personal social space and is within the user's arm length, in which the users can closely observe and directly touch the exhibit. Users are granted privileges of all viewing and interacting with the virtual exhibit.

(2) Observer distance, ranging from 0.6 to 1.2 m from the exhibit. This distance is between the user's arm length and body reach, and assigns the users privileges of viewing and limited interaction.

(3) Passersby distance, ranging from 1.2 to 2.4 m from the exhibit. This distance is out of the user's body reach while still allowing of to exhibit details. Users are granted privileges of limited viewing and limited interaction.

(4) World distance, greater than 2.4 m from the exhibit. This belongs to public space and allows users to quickly pass the exhibit with limited viewing of general exhibit information.

Each distance is associated with a set of privileges of exhibit browsing that comprise the exhibit information and interactive operations the visitors can access. The details of the distances and privileges are summarised in TABLE 1.

TABLE 1. **Distance ranges and related privileges of exhibit browsing**

Distances	Information display	Exhibit Interaction
Operator distance	• Browse all the pages of exhibit • View overall thumb-up LIKE of the categories • View detailed pages' thumb-up LIKE • view videos on the detailed pages	• Manipulate the exhibit (e.g., rotate) • Draw on the virtual exhibit • LIKE the exhibit
Observer distance	• Browse limited pages of exhibit • View overall thumb-up LIKE of the categories • View detailed pages' thumb-up LIKE	• Manipulate the exhibit • LIKE the exhibit
Passersby distance	• View overall thumb-up LIKE of the categories • View detailed pages' thumb-up LIKE	• LIKE the exhibit
World distance	• View overall thumb-up LIKE of the categories	

Visitors can move across the distance ranges during exhibit browsing. For example, when a participant browses a vase, she/he first enters the world distance, where she can view overall numbers of likes of the exhibit but is not allowed to commence any interactive operations. If she is interested and moves forward to the passersby distance, then she can view more information about the vase and gain incremental privileges of interaction. As she continuously moves toward the exhibit into the observer distance, she can see more information about the exhibit and have more interactions. When the visitor reaches the operator distance, she gains all the privileges of exhibit browsing.

As such, the distance-driven user interface allows multiple visitors to browse the exhibit asynchronously. Whenever a visitor arrives at a distance range, she/he automatically gains corresponding access to the exhibit information and interaction that are shared by other visitors. For example, a visitor sees real-time numbers of thumbs-up LIKE of the target exhibit, and she/he can click the LIKE button either synchronously or asynchronously. Thus, the distance-driven user interface supported both in-scene visitors and off-scene latecomers.

The user-exhibit distance is measured as the space between the augmented reality headset and the exhibit. Based on ARcore SDK and the rear camera of the Google Pixel 3 mobile phone, we developed a mobile application that can locate a target exhibit on a desk and estimate spatial distances between the mobile phone and exhibit. FIGURE 2 illustrates the scene of how the user-exhibit distance is detected.

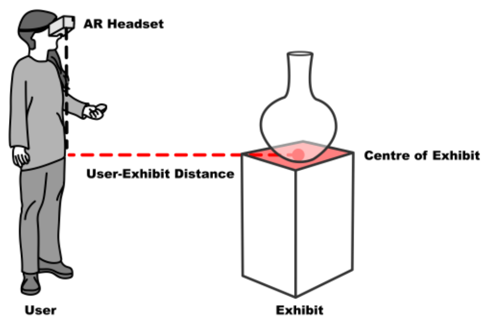

FIGURE 2. **Detection of user-exhibit distance**

2) GRAPHIC USER INTERFACE

According to the exhibit egocentric distance, we developed a set of graphic user interfaces. The graphic user interfaces were developed with Unity3D and the integral algorithms of Holokit [52]. Taking the nine-peach vase as an example (FIGURE 3.), we designed an overall page with nine square tiles as the first entrance page. Each tile represented a category of exhibit information such as history, craft, and materials. As FIGURE 3. shows, the overall page was displayed beside the vase in augmented reality. To ensure accessibility of the user interfaces, the overall page sizes and orientations were designed to be adaptive to the viewer's standing positions, which constantly faced visitors during exhibit browsing. In addition, the tiles were designed with a thumb-shaped background, and their sizes were dynamically updated according to the tile's current numbers of thumbs-up LIKE. For example, the tile for video had the largest thumbs-up shape because the video page received the most thumbs-up clicks on its detailed page. At the bottom of the overall page was a reminder message that indicated other visitors' interactions with the current exhibit.

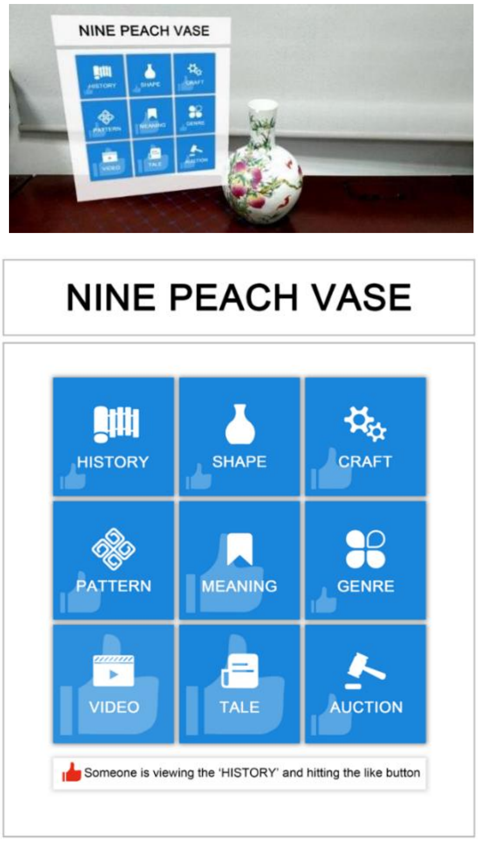

FIGURE 3. **Vase nine-peach and augmented reality graphic user interfaces (top: scene of vase and overall page, bottom: user interface of overall page)**

When the specific tiles of the overall page were clicked, the detailed pages popped up. For example, when the CRAFT tile was clicked, the detailed page of the vase craft opened (FIGURE 4.). The detailed page consisted of three parts. On top is a title bar that displays the name of the current page. The left main part contained the detailed content, which was fitted to one page with texts, pictures, and videos. The contents were static, and the video automatically started to loop when the page was open with sufficient privileges. On the right side was a thumbs-up LIKE button with a current count of LIKEs. Visitors could click the button if they were in favour of the page. The visitors could use the remote controller to navigate back to the overall page.

Visiting detailed pages requires specific privileges that were determined by the visitors' current standing positions. For example, a visitor standing at the world distance can only browse the overall page, and she/he would receive a text reminder when attempting to access the detailed pages (FIGURE 4). By contrast, a visitor standing at the operator distance has full privileges of viewing the overall page and all detailed pages, and visitors in other distance ranges have tapered privileges of accessing detailed pages. All tiles of the overall page are viewable to visitors, and the detailed pages give reminders on necessary occasions. This mechanism is justified for two reasons: first, the overall page serves as the entrance of exhibit browsing and provides equal access to the exhibit with a comprehensive picture of the exhibit; and second, the detailed pages aim to address the visitors' individual interests to the exhibit with differentiated accessibility. An overview of the pages is shown in FIGURE 5.

FIGURE 4. **Detailed page of vase CRAFT**

B. Evaluation of user interface

Participants. We recruited 39 undergraduate and doctoral students from the local university (14 males and 25 females, M_{age} = 22.97, SD_{age} = 1.54), each paid 50 CNY. The participants' backgrounds included computer science, industrial design, and human-computer interaction, all self-reported with normal and correct-to-normal eyesight. In addition, all the participants were asked to fill out a prestudy questionnaire of previous AR experience (see Appendix A). This was to ensure that the participants had an essential understanding of the augmented reality museum. The questionnaire results showed that two participants previously used AR headsets, eight had used mobile phone-based AR applications, and the rest had heard about AR interactions before but never had any practical trials of AR museum systems.

Given that the visitors used to dwell and move in front of exhibit alternatively, the study planned three participant groups, each having a different initial standing distance and that could move freely during the study (group A at the operator distance, group B at the observer distance, and group C at the passersby distance). The fourth group at the world distance was removed from the study, as the distance involves

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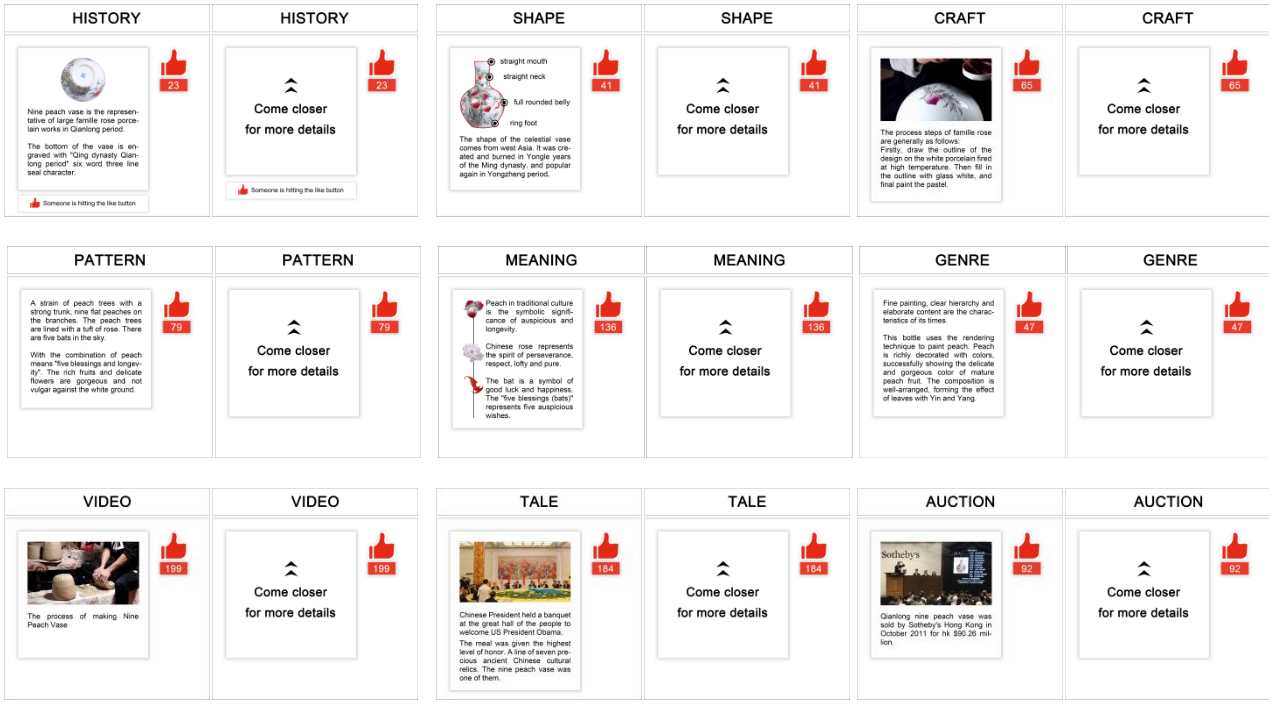

FIGURE 5. Viewing detailed pages with and without specific privileges

only passing-by visitors who have little exhibit interaction. This allowed us to observe how the participants were motivated to change their distance when using the distance-driven user interface.

Apparatus. We built the augmented reality headset by modifying an existing Holokit device [52], which is a low-cost, cardboard-based, head-mounted mixed reality device (FIGURE 6). The original Holokit device was handheld and used a mobile phone to provide augmented reality displays with a 76-degree field of view. We modified the original device by adding head straps to free the participant's hands. Furthermore, we integrated a pair of small webcams in the headset to enable monocular eye tracking (FIGURE 7). Both cameras had 2952×1944-pixel resolutions at 15 Hz, 25×8×3 mm size, and 60-degree field of view.

We modified one camera with infrared sensing lenses to capably capture eye movements in poor illumination inside the cardboard headset. The two cameras were connected to a laptop (CPU 2.3 GHz, 8 GB RAM, Intel Iris Plus Graphics 655) via a standard USB interface for recording and analysing the captured images. The reliability and robustness of eye image capture of the eye tracking module was tested prior to the study. All eye tracking data were recorded and stored locally in the laptop and processed later with Pupil-lab, the open-source eye tracking platform [53].

We attached a Google Pixel 3 mobile phone to the front side of the headset. The mobile phone ran ARcore and Unity programmes, and its binocular screen displays were reflected on the see-through mirror in the headset, so the participant could see a view of the real world overlapping with the corresponding AR content.

The programme calculated the mobile phone's positions relative to the world with concurrent odometry and mapping. It identified the desktop plane on which the exhibit was located to gain positions of the exhibit. The centre point of the square area of the desk plane was selected as the coordinate of the exhibit, and its horizontal distance relative to the origin coordinates of the mobile phone was calculated as the user-exhibit distance. The programme's calculation error was at the centimetre level and was ignored in the study. The frequency of user-exhibited distance detection and interaction privilege updating was 24 Hz.

To assist the participants in browsing exhibit information, we provided a controller that was connected to a mobile phone via Bluetooth (FIGURE 8.). The controller had a joystick for user interface navigation and a set of buttons, e.g., starting navigation asks, entering exhibit pages, going back to previous pages, and thumbs-up LIKEs of current exhibit pages.

FIGURE 6. Mobile phone-based AR headset

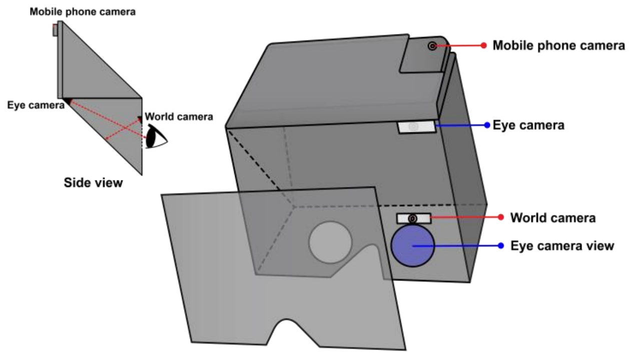

FIGURE 7. Integral eye tracking cameras and mounting positions

FIGURE 8. Remote controller for exhibit browsing

Before the formal study, we tested the usability of cardboard AR headsets to ensure usability and durability. We also optimised the headset with better comfort of wear.

Procedures. The study was prepared in several steps. First, we set up an exhibition scene by placing the nine-peach vase on a table in the laboratory (FIGURE 9.). During the study, we used controlled indoor lights to circumvent unnecessary illumination influence. Light was mounted next to the exhibit to stabilise the illumination of the study (FIGURE 9). Second, we guided the participants to wear the AR headset with oral introductions to the AR museum and study tasks and ensured that the wearing was comfortable and stable. Third, we observed the participants to complete the study tasks and conducted post-study questionnaires. Below we describe details of the procedural flows.

FIGURE 9. Experiment scene

The participants were asked to complete a printed consent form and questionnaires of previous experience before the study. Specifically, the questionnaires collected the participants' previous experience with AR headsets, related preferences, and attitudes toward collaboration in AR museums. They were informed that the exhibit had been simultaneously visited by other participants located in another room who collaborated on interactions such as thumbs-up LIKEs. Then, the participants viewed a short demonstration video to learn their study tasks. Following that was a 2-min practice of headset and remote controller use, which ensured the participants were familiar with all of the interactions.

Eye tracking calibrations were carried out after the practice. The calibration procedures are described as follows. The participants wore the headset and sat approximately 0.5 m away from the laptop screen, and they were instructed to look at nine circles on the augmented display sequentially (FIGURE 10.). They moved to the next circles after the previous one turned green, and the process was repeated until all circles were successfully viewed. The calibration data were processed by the laptop in real time. The captured pupil images were analysed to construct a mathematical transformation between the physical position of the pupil and the spatial point at which the participants were looking.

The participants started the task after eye tracking calibration. The task of browsing had no time constraints, during which the participants could move their standing positions for the sake of interaction. The participants could quit the study whenever they felt enough browsing. The participant activities, including eye movements and interactive behaviours, were recorded on video for later analysis.

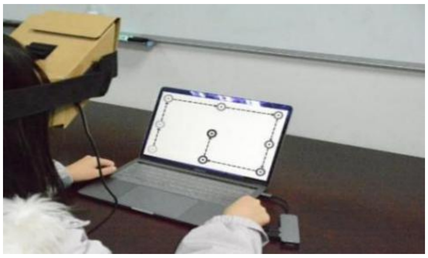

FIGURE 10. **Prestudy eye tracking calibrations**

After the task, the participants were asked to self-report the subjective experience of using the collaborative AR museum and, importantly, the reasons for position movement during the task. During the session, the participants were informed about the overall structure and functions of the AR museum, including how pseudocollaboration was realised. Following that was two questionnaires, one was specialised for perceived usability that was derived from [54] (Appendix B), and another was to measure learning outcomes with proven effectiveness in early studies [55] (Appendix C). After that, the participants received a short semiformal interview by the experimenter, who asked for additional explanations of extremely low/high ratings in the questionnaire, e.g., ratings of 1 or 5.

IV. DATA ANALYSIS AND RESULTS

The study collected both qualitative and quantitative data, which consisted of 117 questionnaires, 39 eye tracking recordings of the three participant groups, and 39 experimental video clips. Given the data, we analysed the influence of the distance-driven user interface on the participants' collaborative exhibit browsing. Specifically, we examined (a) perceived usability, (b) effectiveness of the distance-driven user interface, and (c) the participants' learning gains with respect to learning efficiency and learning experience. Specifically, the learning experience was gauged in four aspects: interpretability, willingness, interest, and engagement of learning. These metrics were derived from early studies on learning experience evaluation, which were proven to be effective in augmented reality museums [55].

A. Perceived usability

We used SUS [54], which examined the aspects of effectiveness, ease of use, and overall satisfaction, to evaluate the perceived usability of the distance-driven user interface. The overall scores of perceived usability across the three groups are summarised in FIGURE 11.. Group B had the highest scores with significant differences compared with the other two groups (Kruskal-Wallis test: df = 2, $p = 0.045$). The paired group test reported significant differences in group A and group B ($p = 0.022$) and in group B and group C ($p = 0.046$). After p-value adjustment in multiple comparisons, no significant differences were found between the groups.

The results showed a high overall perceived usability of the distance-driven user interface, and the overall perceived usability was affected by the participants' standing distance to the exhibit. The results implied that the participants opted to gain higher overall perceived usability at the observer distance. According to the participants' feedback, compared with the other distance ranges, such as operator distance and world distance, the observer distance range sufficiently exhibited interaction privileges and flexibility in exhibiting view adjustment.

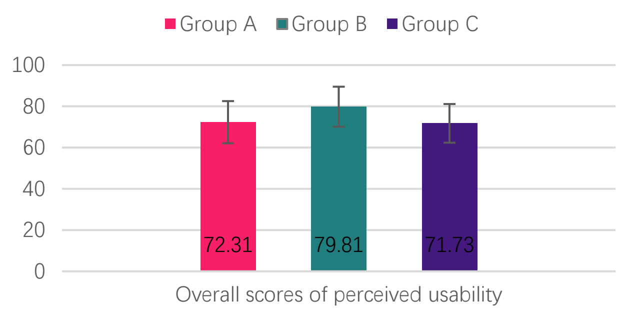

FIGURE 11. **Overall scores of perceived usability across three participant groups**

We analysed the perceived usability with regard to effectiveness (Questions 2, 5, 6), ease of use (Questions 3, 4, 7, 10), and overall satisfaction (Questions 1, 8, 9). The results showed that Group B had noticeably higher scores than the other two groups in all three aspects of perceived usability (FIGURE 12.). However, the Kruskal-Wallis test reported significant differences between group B and the other two groups in terms of overall satisfaction ($p_{satisfaction} = 0.032$), and no significant differences were reported in the remaining aspects (df = 2, $p_{effectiveness} = 0.270$, $p_{learnability} = 0.284$). Pairwise comparisons reported significant differences in the three aspects between group A and group B, group B and group C ($p_{\text{group C vs. group B}} = 0.019$, $p_{\text{group A vs. group B}} = 0.029$). However, no significant differences were found after adjusting the p-value for multiple comparisons. The results indicated that the distance ranges had inconsistent influences on the aspects of perceived usability.

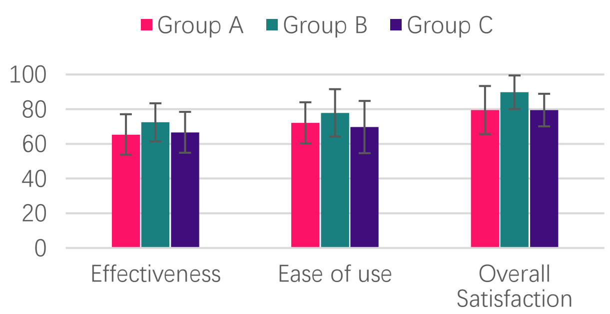

FIGURE 12. **Scores of perceived usability in specific aspects**

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One important goal of the distance-driven user interface was to stimulate deeper and longer participant engagement with the exhibit, e.g., whether the participants were motivated to move toward the exhibit for closer interaction. To understand why and how the participants adjusted their standing distances to the exhibit during the study, we manually transcribed experiment video footage and annotated interview logs. The results showed that 10 of 13 participants in group B and 11 of 13 participants in group C moved toward the exhibit for more collaborative interaction.

The remaining participants did not move because they felt that they were not explicitly invited to do so during the study, although they indicated a willingness of movement in interviews. Although group A was at the nearest distance with less space for further movement, 3 participants moved back and forth for closer observations on the exhibit, and others mostly stood at their initial positions. The observation results showed that most participants, implicitly or explicitly, were motivated by the distance-driven user interface to participate more in the collaborative exhibit browsing.

B. Learning Gains

Learning gains are recognised as an important metric due to the museum's nature as a learning institution for the public [55]. To understand the participants' actual learning gains during the study, we evaluated the participants' learning efficiency, duration of learning attention, and overall satisfaction.

1) LEARNING EFFICIENCY

Learning efficiency is a key dimension of museum learning [56], which indicates how quickly the participants perceived exhibit information through exhibit browsing. To reflect learning efficiency, we calculated how many user interfaces—the overall page and detailed pages—were viewed by the participants during the tasks. The three participant groups visited different numbers of pages, but no significant differences were reported (FIGURE 13.).

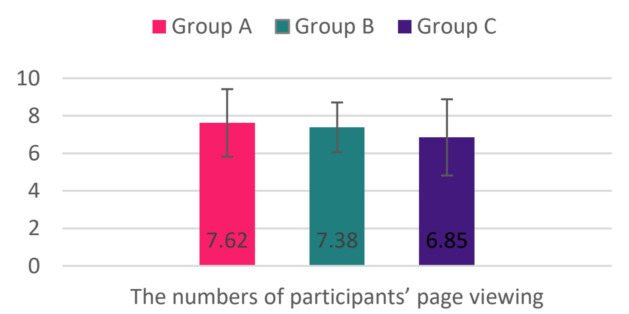

FIGURE 13. Numbers of participants' page viewing

Second, we examined the participants' durations of overall page viewing (FIGURE 14.) and found significant differences between the three groups (Kruskal-Wallis test $p = 0.008$). Furthermore, pairwise comparisons indicated that group A and group C had significant differences ($p_{\text{group C vs. group A}} = 0.008$). The results showed that the distance-driven user interface had different impacts on the participants' learning efficiency with respect to page reading durations. The results in FIGURE 14. displayed an observable decreasing trend of page viewing durations from group A to group C. Taking into account these groups' initial standing distances, it is not unreasonable to infer that the participants who stood at a closer distance were more likely to be engaged longer in exhibit browsing.

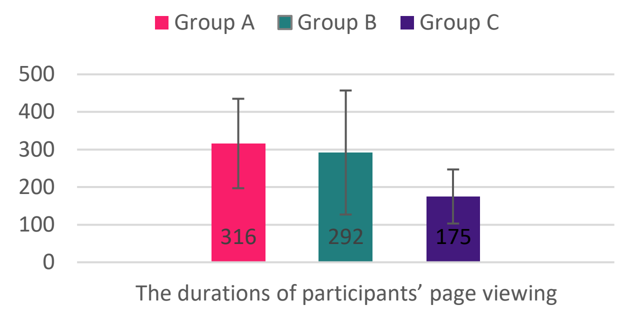

FIGURE 14. Durations of participants' page viewing

Third, we calculated the three groups' durations of detailed page viewing, which lasted 158 sec on average and accounted for 58.78% of all page viewing. By contrast, the overall page durations of viewing were 90 sec (37.66% of all page viewing). The Kruskal-Wallis test reported significant differences in durations of detailed page viewing across the three groups (df = 2, $p = 0.008$), and pairwise comparisons confirmed the significance difference between group A and group C ($p_{\text{group C vs. group A}} = 0.009$). The results, again, implied that the participants' engagement with AR museum exhibits was correlated with the distance This was associated with interaction privileges such as exhibit viewing and manipulating.

In addition, the detailed pages with pictures and videos had longer durations of viewing (page 6, $p = 0.044$, $p_{\text{group C vs. group B}} = 0.048$; page 7, $p = 0.001$, $p_{\text{group C vs. group A}} = 0.000$; page 8, $p = 0.005$, $p_{\text{group C vs. group A}} = 0.004$; page 9, $p = 0.017$, $p_{\text{group C vs. group A}} = 0.038$, $p_{\text{group B vs. group A}} = 0.041$). During detailed page viewing, we found that the most frequent operations were selecting pages and clicking the LIKE button (df = 2, $p = 0.186$), but the frequencies were not different between the groups. We measured how quickly the participants began to interact with the detailed pages after the task started. Speed seemed to be an explicit indicator of learning engagement because the participants began to proactively seek relevant information in exhibit browsing. The results showed significant differences in speed across the three groups (Kruskal-Wallis test, df = 2, $p = 0.022$), and pairwise comparisons confirmed the significant differences between group A and group C ($p_{\text{group C vs. group A}} = 0.035$).

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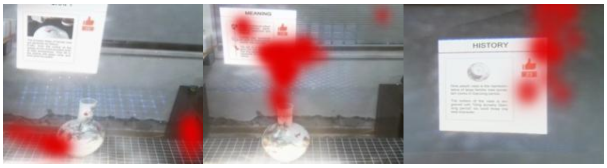
(a)



(b)

(c)

(d)

FIGURE 15. Eye tracking heatmaps of overall page and detailed pages

To understand how the participants looked at the user interface during exhibit browsing, we extracted video clips of the participants' eye movements and calculated eye gazes to generate heatmaps (FIGURE 15). The video clips consisted of a collection of experimental scenes when the participants looked at the graphic user interfaces at a relatively static position. Other video clips were removed because of less accurate detection of the participants' visual attention during body movement. By visualising the eye gaze coordinates into red points, we generated the heatmap.

The eye tracking heatmap showed that the three participant groups had similar visual attention focused on the tiles of interest (FIGURE 15-a). The thump-up in the tiles drew the participants' attention and influenced their choice of tiles, which was also confirmed in semiformal interviews. It also showed that the participants without specific interaction privileges had much lower visual focus on the detailed pages (FIGURE 15 -b and -c). The participants understood the meaning of the text in a relatively short time and returned to the overall page promptly when they were presented with the reminder message (FIGURE 15-d). Some of them noticed an increase in LIKE during a short stay on the page.

2) LEARNING ATTENTION

Eye blinking is a proven indicator of learning attention in information processing [57]. Specifically, a high frequency of eye blinking implies a low cognitive load, and vice versa. Therefore, we calculated participants' eye blinking frequency with eye tracking data in the following equation:

$$F = \frac{T_o}{N_e}, \tag{1}$$

where F is the eye blinking frequency, Ne is the overall eye blinking number, and To is the overall duration of eye blinking. The results are summarised in FIGURE 16 The results reported that group C had a higher frequency than the other two groups, and group A had the lowest eye blinking frequency.

Furthermore, group A had a lower eye blinking frequency when browsing detail pages and a higher eye blinking rate with overall pages. The results implied that distance influenced the participants' cognitive attention performance. However, no significant differences were reported between the three groups.

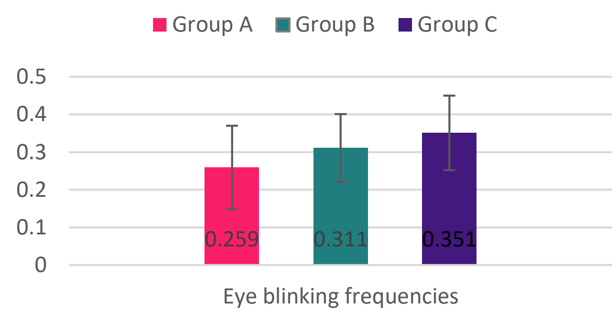


FIGURE 16. Eye blinking frequencies

3) LEARNING SATISFACTION

We derived four metrics (interpretability, willingness, interests, and engagement) [55] to measure the participants' overall learning satisfaction during collaborative exhibit browsing. Each metric is evaluated with three questions (see questions in Appendix C). The results are summarised in FIGURE 17. No significant differences were reported across the groups, implying that the distance-driven user interface had little influence on the participants' overall experience.

The questionnaires provided additional qualitative results regarding the participants' perceptions of the augmented reality museum with a distance-driven user interface. For example, many participants were not fully aware of the user-exhibited distance and related interaction privileges (Q1: M = 3.62, SD = 0.99), and several participants did not feel that the distances reflected their interests in the specific exhibit (Q2: M = 3.79, SD = 1.15). The LIKE was easy to understand (Q3: M=4.38, SD=0.88).

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Most participants were motivated to move closer to the exhibit (Q5: M=4.18, SD=0.82), although there was insufficient quantitative evidence revealing the influence of connotative information of the user interfaces (Q8: M=3.13, SD=1.15). Based on the numbers and frequencies of LIKE button clicking, the participants reported that they were likely to be drawn to pages with higher popularity (Q9: M=4.26, SD=1.07), and their collaborative interactions would help others' browsing experience (Q6: M=4.08, SD=1.11). A few participants expressed their concerns about system usability when browsing the exhibit with the augmented reality user interface displayed aside it, although no technical difficulties were encountered during the task (Q4: M=3.69, SD=1.00).

C. Summary of results

The study results are summarised in **Error! Reference source not found.**. Given the analysis results, the study showed that the overall perceived usability scores were significantly different from one distance to another, indicating that the distance-driven user interface did not have a consistent degree of usability across the distances. Regarding learning gains, the results showed that learning efficiency was significantly different across the four distance ranges. Specifically, close distances used to have long durations and fast browsing speed of exhibit browsing. That is, the participants were stimulated to engage in asynchronous collaborative exhibit browsing with enhanced learning efficiency and learning attention. Given the results, hypothesis 1 is denied, and hypothesis 2 is partially denied.

TABLE 2. **Summary of study results**

Metrics		Results
Perceived usability	Overall usability	no significant differences between the three groups
	Effectiveness	no significant differences between the three groups
	Ease of use	no significant differences between the three groups
	Overall satisfaction	no significant differences between the three groups
Learning gains	Learning efficiency	durations of overall page viewing：significance difference between group C and group A durations of detailed page viewing：significance difference between group C and group A how soon the participants started to interact with the pages：significance difference between group C and group A the detailed pages with pictures and videos received：significant differences between the three groups
	Learning attention	no significant differences between the three groups
	Learning satisfaction	no significant differences between the three groups

V. DISCUSSION

The study investigated how the distance-driven user interface affected collaborative exhibit browsing in an augmented reality museum context. This shows that the user-exhibit distance played an essential role in a communication medium that effectively stimulated collaborative interaction. The study confirmed the effects of user-artefact spatial distance that positively enhanced system usability, user engagement, and learning efficiency [32], which were consistent with early studies on proxemic interaction and distance-based user interfaces such as [4], [9], and [11].

Moreover, the study furthers the current understanding of user-exhibited distance in collaborative exhibit browsing. Specifically, it reveals a significant influence on perceived usability and learning performance across the distributions of distance, while it also indicates variant effects on different aspects of usability and learning. For example, group B in

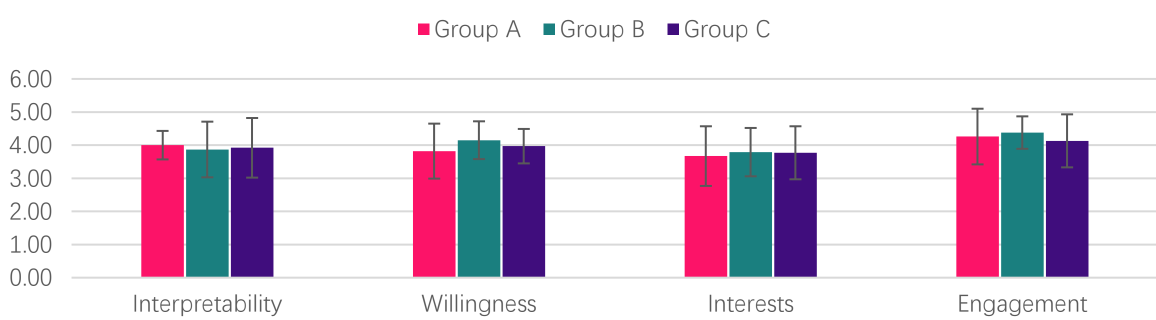

FIGURE 17. **Questionnaire results of participants' overall satisfaction**

observer distance gained constant leading advantages over the other two groups in perceived usability, whereas significant differences were reported only in the overall ratings and the aspect of satisfaction of perceived usability. Despite significant improvement in learning efficiency, no significant difference was found in the aspect of learning satisfaction. Below, we elaborate on these findings to highlight implications for collaborative exhibit browsing.

Unlike previous studies that used to focus on distance distributions and related influence on system usability and user engagement, the novelty of this study is that it integrated social networking features, e.g., LIKE buttons with distance ranges. This brings three practical benefits. First, the participants were continuously reminded by the LIKE buttons in the overall and detailed pages, which were simultaneously visited by other remote users, and all data were synchronised across the users in real time. This ensures users' awareness of collaborations while browsing and enhances overall user engagement.

Second, the integral social features act as an indicator of the current distance ranges in the study as well as a reminder of adjusting standing positions to access more (or less) information and operations. This drives users to move toward the exhibit in an understandable manner, as a short distance socially and psychologically refers to close-interaction relationships. Third, the combination of social network features and distance ranges gives participants a sense of obligation to browse more pages of an exhibit for prolonged durations. All participants mentioned in interviews that they wanted to browse the exhibit more when they realised that interaction privileges changed accordingly with standing distances. In particular, as indicated by FIGURE 13. and FIGURE 14., the sense of interaction obligations seems to be strong at a close distance.

The study results show that the overall scores of perceived usability vary from one distance range to another, indicating that perceived usability may be affected by the distance-driven user interface. The difference seems to be attributed mainly to the aspect of overall satisfaction, as the overall perceived usability reports no significant differences when we remove overall satisfaction from overall perceived usability scores. This result is consistent with the study results that the aspects of effectiveness and ease of use are not different across the distance ranges. The difference in overall satisfaction is justified for one reason, as group C standing at passersby distance see only limited information and frequently respond to the message 'move closely for more operations' when attempting to interact. This explains why the difference in overall satisfaction between group A and group C is greater than that between group B and group C.

In addition to the distance ranges, user interface design also leads to consistent results of effectiveness and ease of use. For example, all graphic user interfaces (see FIGURE 3. and FIGURE 4.) are set to face participants throughout exhibit browsing, and related elements, e.g. icons and texts, are kept accessible regardless of distance adjustments. Given these understandings, it is not unreasonable to claim that the distance-driven user interface is capable of simultaneously delivering consistent usability to participants at all distance ranges, although hypothesis 1 is statistically denied.

Regarding the results of learning gains, we notice that participants' learning efficiency is the only aspect that is mostly affected by the distance-driven user interface. Specifically, the groups standing at a close distance to the exhibit, e.g., group A, tend to have longer durations of exhibit viewing. This result is justified for two main reasons. The first is that participants at a close distance are given more information display and interaction privileges, which increases the overall number and durations of exhibit pages.

The second is that the participants spent some more time on social networking interactions, such as clicking the LIKE button. Interestingly, we found that participants at a close distance were faster to start viewing the exhibit, but this did not make a significant difference in participants' cognitive loads. This verifies the distance-driven user interface's effectiveness in dissimilative information displays. Learning attention and learning satisfaction were less influenced in the study. This means that the information display and interaction privileges distributed at different distances match properly with participants' needs to exhibit browsing, which again confirms the model's effectiveness.

The study demonstrates that the distance-driven user interface is effective in stimulating collaborative exhibit browsing, as over 77% of participants moved toward the exhibit for more information and interaction, and the rest expressed explicit willingness of movement during the study. The results are mainly attributed to distance ranges that integrate social networking features. As the post-study interviews reflect, the participants are likely to be motivated to approach the exhibit to see how it interacts with other users.

The study does not show solid evidence of whether and how participants' movement influences perceived usability; however, it indicates that the forward movement benefits participants' learning efficiency. As such, the user-exhibit distance is not only an indicator of interaction relationships—which is often considered in previous studies—but is also a measurement of interaction motivation. Taking into account the participants' frequencies and durations during exhibit browsing, we notice that the participants are extraordinarily interested in pages recommended by other users. In addition, the participants supplied in interviews that they were willing to follow the system when prompted to approach the exhibit closely, which was also attributed to collaboration exhibiting browsing.

Our study provides some practical implementations for augmented reality museum design. First, it provides a new model for user-exhibit interaction which is easy to implement without significant infrastructure change in existing museums. Second, evaluation of the model adds new understanding of how such an interaction model affects collaborative exhibit browsing with respect to perceived usability and learning gains. For example, asynchronous information displays and interactions raise participants' awareness of other users, and awareness is likely to enhance participants' attention to learning. In other words, asynchronous communication does not distribute a task to multiple users to accelerate overall task completion but motivates participants to explore more exhibit pages on an individual basis.

Given the above implications, the distance-driven user interface is generalised in other interaction scenes. This is justified for two reasons. First, the distance and social networking features are compatible with many other public sites such as art galleries; second, the distance-driven user interface delivers different exhibit information and interaction privileges to individual users, and this will inevitably drive users to acquire and share more information in an asynchronous collaboration manner.

The study has several limitations with respect to experimental settings. For example, the participants viewed the exhibit, an antique vase, from only one open side. By contrast, realistic exhibit browsing is omnidirectional. Given our study results, we anticipate that users might be more actively adjusting their standing distances toward the exhibit. However, this does not impair the reliability and validity of our study, as users' interactions are based on an augmented reality system. In addition, a few participants complained about ergonomic discomfort caused by the weight of the augmented reality headset. Admittedly, discomfort might be exaggerated after long-term use and may have an unexpected influence on perceived usability. Although we did not observe any significant impacts of the headset in the study, optimising the headset design is an important future task.

Despite the preceding findings, the study requires further research with regard to designing and understanding the distance-driven user interface across a wide range of applications. For example, it needs to be further investigated how the distance-driven user interface works with virtual avatars of multiusers in augmented reality museums. This involves multiple interaction modalities such as eye gaze and hand gestures and provides visitors with finer experiences of immersive museums. Also needing exploration is the generalisation of applications of the distance-driven user interface. After all, there are many interaction tasks and scenarios that have dynamic user locations.

VI. CONCLUSIONS

In this paper, we proposed a design evaluation of a distance-driven user interface for asynchronous collaborative exhibit browsing in an augmented reality museum. The user interface utilised the user-exhibit distances that were divided into four ranges to leverage collaborative exhibit browsing. The paper presented comparative studies that explored the influence of the user interface on perceived usability and learning gains. The results showed no differences among the three groups with respect to perceived usability and learning attention, but there were significant differences in learning efficiency. Specifically, participants whose initial standing position was nearest to the exhibit had higher learning efficiency than the others, indicating that the distance-driven user interface can effectively drive the participants to move closer to the exhibits to achieve more detailed information with higher learning efficiency.

APPENDIX

Appendixes are enclosed for reference.

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