Kobeisse, Suzanne ORCID logoORCID: https://orcid.org/0000-0001-8566-1032 (2024) Hands on the Past: Towards a Conceptual Framework for Developing and Evaluating Tangible AR Interfaces for Historical Artefacts. In: OzCHI2023: Design from a distant world, 2 - 6 December 2023, Te Whanganui-a-Tara, Wellington, Aotearoa, New Zealand. ISBN 9798400717079

Official URL: http://doi.org/10.1145/3638380.3638445
DOI: http://dx.doi.org/10.1145/3638380.3638445
EPrint URI: https://eprints.glos.ac.uk/id/eprint/14106

Hands on the Past:

Towards a Conceptual Framework for Developing and Evaluating Tangible AR Interfaces for Historical Artefacts

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This paper presents a conceptual framework for tangible AR interfaces to manipulate historical artefacts. Advances in digital technologies exalted tangible interfaces and augmented reality applications into the museum scene. However, there is a lack of well-defined design space that formalises the design process of tangible AR interfaces. The framework is evaluated and refined by analysing data collected from an in-situ study for a tangible AR exhibit at a museum (N=80) and presents key aspects that contribute with a set of design characteristics for developing and evaluating tangible AR interfaces. The proposed framework aims to promote tangible AR interfaces that foster a sense of engagement, facilitate learning, and enhance interaction experience with historical artefacts. Additionally, the framework can aid designers, researchers, and cultural heritage professionals in understanding and guiding the design process to build more engaging tangible AR interfaces that are specific for the manipulation of historical artefacts.

CCS CONCEPTS • Human-computer interaction (HCI) ~ HCI theory ~ Concepts and models • Human-computer interaction (HCI) Interaction Paradigms ~ Mixed/augmented reality

Additional Keywords and Phrases: Tangible Interfaces, Augmented Reality, Conceptual framework, Cultural Heritage

ACM Reference Format:

First Author's Name, Initials, and Last Name, Second Author's Name, Initials, and Last Name, and Third Author's Name, Initials, and Last Name. 2018. The Title of the Paper: ACM Conference Proceedings Manuscript Submission Template: This is the subtitle of the paper, this document both explains and embodies the submission format for authors using Word. In Woodstock '18: ACM Symposium on Neural Gaze Detection, June 03–05, 2018, Woodstock, NY. ACM, New York, NY, USA, 10 pages. NOTE: This block will be automatically generated when manuscripts are processed after acceptance.

1 Introduction

A common sight in museums is "do not touch" signs to deter visitors from touching heritage collections on display. However, digital technologies intervention in museums has developed significantly to promote interactive and immersive experiences to engage visitors with historical objects [48, 19, 28, 11]. Additionally, the shift towards forging connections with the historical artefacts through their material properties to evoke personal feelings and to elicit learning has yielded in-depth discussion in museology [3, 7, 40, 42]. While numerous museum exhibitions provide visitors with tangible interaction and immersive experiences, whether using touch displays, smart replicas, or 3D-prints of original artefacts, these exhibitions mainly still focus on specific systems development and lack widespread implementation. Consequently, the design space for tangible AR interfaces to manipulate historical artefacts remains an underdeveloped area. This paper presents a conceptual framework for tangible AR interfaces to manipulate historical artefacts by analysing data collected from an in-situ study at a museum (N=80) for a tangible AR exhibit, as a practical case study to evaluate and refine the framework.

The framework concepts are elucidated from theoretical literature in relation to HCI field such as tangible user interfaces, augmented/mixed reality and gesture interactions. The exhibit is a *walk-up-and-use* tangible AR exhibit that offers museum visitors the ability to manipulate and interact with interpretation of historical artefacts using physical objects as generic proxies. The tangible AR exhibit aims to promote an intuitive interaction experience and remove the physical barrier between the visitors and the historical artefacts. The exhibit is a result of a collaborative research project involving the author and a museum set within a heritage site and its staff, including the exhibitions manager, engagement officers, a team of data and digital officers, as well as heritage professionals and archaeological experts. In August 2021, the museum installation was showcased as a stand-alone exhibit in the museum's permanent exhibition space and was experienced by visitors of various age groups (see Figure 1).

Figure 1: The museum visitors of different age groups interact with the tangible AR Exhibit.

The visitors' data was analysed using Thematic Analysis [2]. Accordingly, four core themes were identified: Interactivity, Engagement, Learning, and Usability, and four main concepts: Tangible Interfaces, Gesture Interactions, Mapping, and System Design. The main concepts are aligned to ten key aspects: *Manipulation, Control, Feedback, Communication, Rewarded Experience, Making Connection, Accessibility, Visibility, Efficiency, Consistency*. The key aspects contribute with a set of design characteristics that are implemented into the tangible AR exhibit. The theoretical scaffold provides a systematic classification of design characteristics for tangible AR interfaces that potentially would benefit researchers, designers, and cultural heritage professionals and offer them a common language to discuss and identify important aspects of the design process to develop engaging tangible AR interfaces that are specific for manipulation of historical artefacts. While previously, frameworks in HCI have been developed to analyse tangible interaction, however no frameworks to date have been developed with the aim to develop and evaluate tangible AR interfaces specific to manipulation and direct interaction with historical artefacts. Particularly, the rapid development of digital technologies in museums, where guiding the design process for tangible AR interfaces becomes a more significant area of research. Therefore, the main contribution of this paper is to provide a formalised approach in which focuses on understanding and guiding the development and evaluation of tangible AR interfaces to manipulate historical artefacts.

The next section presents the related work that informed the tangible AR exhibit and the conceptual framework. Then the section on the collaboration with a museum. Followed by a detailed account of the in-situ study design and data analysis methods. Finally, the conceptual framework is presented with the identified core themes, main concepts, and key aspects that can be implemented into a tangible AR exhibit for historical artefacts. The paper concludes with future research opportunities and conclusion.

2 Related work

2.1 Tangible Interfaces and Augmented Reality

Tangible interfaces refer to physical objects that are embedded with digital information, which utilise the physical objects both as representations and controls for computational media [18]. TUIs also benefit from humans' natural skills to grasp and manipulate physical objects. The concept of Graspable User Interfaces was first introduced by Fitzmaurice et al. (1995) in "Laying the Foundations for Graspable User Interfaces" bricks – an input system that allows direct manipulation of virtual objects through physical handles using two-handed interactions, offering a seamless blend between the physical and virtual worlds [13]. The Graspable User Interface aimed to introduce new design spaces based on existing skills of humans' abilities gained from using GUIs and therefore as a means of augmenting the power of conventional Graphical User Interfaces.

On the other hand, tangible AR interfaces refer to an interface where a virtual object is registered to a (tangible) physical object; the user can interact with a virtual object by manipulating the corresponding tangible object [21]. Given the familiarity and affordances of everyday physical objects and the advantages for the user to make the associations between physical objects and digital content [34], tangible interfaces provide a suitable interface to interact with virtual AR objects. Early research into tangible AR adopted interaction principles from tangible interfaces such as the support for physically based interaction techniques, like using object proximity or spatial relations), a match between the physical constraints of the object to the task requirements, support for a parallel activity where multiple objects or interface elements are being manipulated at once, and collaboration between multiple participants [1]. One example is the Magic Paddle [22], a tangible AR book that allows users to manipulate virtual objects in a virtual scene. By using a physical cardboard paddle as an interaction device, users can copy and transfer virtual furniture pieces from the book pages onto a large piece of paper that represents the virtual room.

2.2 Digital Technologies Applications in Cultural Heritage

Tangible interfaces and augmented reality applications in museums have ranged from the use of augmented reality to build virtual museums [47] to physical tokens and smart artefacts [4, 31] to tangible augmented reality applications such as The Loupe which uses a magnifying lens with an embedded smartphone to overlay virtual content by scanning a nearby QR code next to the original artefact [43]. Wakkary et al., (2009) [45] explored the use of multiple tangible devices to support social interactions of family members in a museum visit. More recent research uses generic physical objects for augmented reality which allows users to grasp physical objects and inspect digitised historical artefacts through their mobile phone display [25, 27, 30]. Virtual reality (HoloLens) was also studied as an approach to promote learning with virtual archaeological artefacts [38]. Research also suggests that augmented reality offers a higher level of presence when interacting with historic artefacts [8]. Furthermore, Cube Museum AR [33] a cube-shaped tangible AR interface which consists of six acrylic cards with image targets that allow the user to scan the cards and view virtual objects of cultural artefacts or trigger information about the artefacts via a mobile AR application. Similarly, [20] also developed a cube-shaped tangible AR interface that facilitates remote access to archival research by scanning QR codes attached to the cube. Both works restrict the user interface to the mobile screen. This indicates that the user is unable to fully (physically) interact with the virtual object as the user still needs to press buttons on the screen to release information. Hence the conceptual framework presented in this paper can aid to formalise the design process that supports the development of tangible AR interfaces using the framework's key aspects that are aligned with a set of design characteristics to promote full immersion with the virtual object by keeping the user's hands on the physical object to access further information about the artefacts.

2.3 Tangible Interaction Frameworks

Following data-centered approach for developing systems in the domain of tangible interfaces, a shift was made towards a focus on more theoretical framing in order to understand the analytical aspects behind these systems. Early tangible interfaces frameworks addressed the various properties of tangible interfaces [41], as well as taxonomies, such as the use of metaphors [12], embodied and social interactions [15], and designing tangible interaction systems for collaborative uses [16].

The related work revealed that most of these frameworks focus on identifying the analytical configuration, as well as designing and building complex data-driven systems typically for the domain of engineering and computer science. While tangible interfaces applications in museums have made great progress, however, theoretical frameworks specific to tangible interfaces remain scarce. The frameworks found in the literature, address more holistic considerations for technological use such as toolkits to facilitate rapid prototyping [37] or general exhibition design [6, 9]. On the other hand, the conceptual framework presented in this paper aims to present a formalised approach to address the development and evaluation of tangible AR interfaces that are specific for the manipulation of virtual representations of historical artefacts, which to the best of the knowledge of the author, have not been examined in any prior works. Therefore, through this knowledge gap, this paper contributes with a conceptual framework that aims to leverage the design space for developing and evaluating tangible AR interfaces.

3 The museum installation

The tangible AR exhibit was developed in collaboration with a museum. Subsequently, every aspect of the exhibit was developed through an iterative process and co-designed with stakeholders with specific requirements to ensure that the interpretive approach represents the landscape where these historical artefacts were excavated. The museum provided access to download their collection of 3D models of digitised Bronze Age artefacts which were generated through a combination of 3D scanning and photogrammetry techniques. The exhibit consisted of a box with a tablet installed on top of the box with a built-in AR application. The user can view virtual representations of historical artefacts by scanning image targets attached to cylinder-shaped generic proxies. Additionally, the user can view and select information about the artefacts using gesture interactions by moving or rotating the generic proxies. This unique approach to tangible interfaces for AR allowed for full immersion with the historical artefacts as the user interactions are not moved away from the physical object in their hand.

The museum installation was as displayed as a stand-alone exhibit for two weeks in the museum's permanent exhibition space. The museum serves as a gateway for the people visiting the region National Park, it also houses a series of interactive exhibits including touch screens and tangible interaction exhibits that encourage visitors to learn about the different topics related to the natural habitat and topographical structure of the landscape.

During the two-week installation, the visitors were invited to interact with the tangible AR exhibit and have hands-on experience with a collection of Bronze Age artefacts using generic proxies and an augmented reality application. The visitor can pick any of three cylinder-shaped generic proxies, and place them inside the box, enabling them to physically engage with the historical artefacts and closely examine their details. Each generic proxy represents one of the three virtual 3D models (an urn, a food vessel, and a beaker). The visitors can also access the artefacts' interpretation using gesture interactions as output modalities in AR to uncover photographs, maps, and text, as well as listen to audio narrations.

4 in-situ study design and methods

The study took place at a museum between August 9th and August 22nd, 2021. The study aimed to examine how museum visitors responded to tangible AR interfaces to manipulate historical artefacts and their overall experience with the exhibit. The study adhered to all COVID-19 safety measures to safeguard the visitors. The study took place over two weeks including two weekends. According to the visitor visit data, the museum was receiving approximately 600 visitors per day. Although the museum had confirmed that their visitor footfall was much higher pre-pandemic.

4.1 Methodology

The visitors were left to freely interact with the exhibit and they weren't given any specific guidance or instructions besides the written instructions on the exhibit banners. The researcher was present in the permanent exhibition space during the exhibit period and only stepped in to provide additional support in case visitors had any questions or would want to offer feedback and comments on the exhibit. The researcher also used informal interviews to capture some of the visitors' reactions and verbal feedback which were all noted down and included in the data analysis to develop further insights related to the framework. The visitors were provided with an information sheet explaining the study and were asked to fill out a questionnaire, including questions about their demographics, such as gender, age, occupation, and their experiences with AR/VR applications. The questions were designed to encourage the participants to describe their overall experience. The following three questions were used:

1. How would you describe your overall experience with the exhibit?
2. Did you learn anything interesting about the Bronze Age artefacts?
3. Would you like to see other historical artefacts interpreted using the exhibit?

As the exhibit took place during the COVID-19 pandemic, all visitors and staff followed the required local government guidance regarding safety and social distancing. Before the exhibit, the researcher submitted an ethics application and was approved by the University's ethics committee. The visitors were photographed while interacting with the exhibit and were asked to sign a consent form on the use of their photographs for academic dissemination purposes. The permanent exhibition space had a one-way system and a limited capacity of 15 visitors. Visual instructions on 2m distancing, and hand sanitiser cleaning points at entrance/exit points were clearly marked. Pens were also provided for the completion of the questionnaire and were cleaned after each usage.

Paper questionnaires were used to collect visitors' responses and analyse the written data. Additionally, the researcher observed visitors from afar to capture their initial reactions. The questionnaire addressed the visitors' overall experience with the exhibit, whether they learned something new about the historical artefacts, as well as if they anticipate different uses for the Exhibit in other domains as well. Additionally, a digital survey display was placed next to the Exhibit to rate the visitors' satisfaction including emojis, as well as answering three Likert-type scale questions: 1) after using the exhibit, I felt like I interacted directly with the Bronze Age artefacts; 2) I learned something interesting about the Bronze Age artefacts using the exhibit; 3) tangible interaction and Augmented Reality for historical artefacts is an engaging approach. The digital survey application entries showed that 572 visitors interacted with exhibit, indicating that the visitors actively engaged with exhibit.

4.2 Participants

Overall, 80 visitors (40 female and 40 male) with an average age of 42, filled out the paper questionnaire. Occasionally, visitors engaged with the researcher in a discussion about the exhibit and the technological approach for exploring historical artefacts, in which the researcher took notes of their verbal comments, adding more richness to the data, beyond their initial written feedback in the questionnaire. Sixty-three visitors have university-level education with various occupations, such as teachers, office administrators, engineers, doctors, university lecturers, architects, and local government officers. In terms of previous AR/VR experience, fifty-five visitors had previously used an augmented reality application (i.e., Snapchat, IKEA) or VR commercial headsets and controllers inside and outside the museum context, and although more senior visitors tended to have less AR/VR experience, they were still interested to experience new technologies.

4.3 Data Analysis

The data analysis was conducted using mixed methods of data collection combining a paper questionnaire and a self-completed digital screen survey. The data was analysed using Thematic Analysis following an inductive approach with no pre-set themes prior to the coding process in order to identify relevant themes. The researcher started by reading through the whole transcripts in detail to develop an overall understanding of the data direction and explore visitors' additional responses. To strengthen the process related to the method and analysis design, several readings were repeated to identify recurring concepts and construct potential meanings across the data, enabling a rich understanding and development of the findings [2]. The next section describes the conceptual framework which was evaluated and refined using the data analysis.

5 The conceptual Framework

The conceptual framework is evaluated and refined by analysing data collected from the in-situ study at a museum. The framework is illustrated using a visual diagram as shown in Figure 2. The visual diagram indicates four overarching core themes, that encompass the four main concepts which are later defined and thoroughly discussed. Hereafter, each main concept is connected to its corresponding key aspects. The key aspects contribute with a set of design characteristics as detailed in Table 1 to guide the design process and support practical implementation of tangible AR interfaces to manipulate historical artefacts. The centre of the visual diagram situates the initial component, which are the artefacts 3D models that can be incorporated within tangible AR exhibit using the design characteristics proposed by the framework.

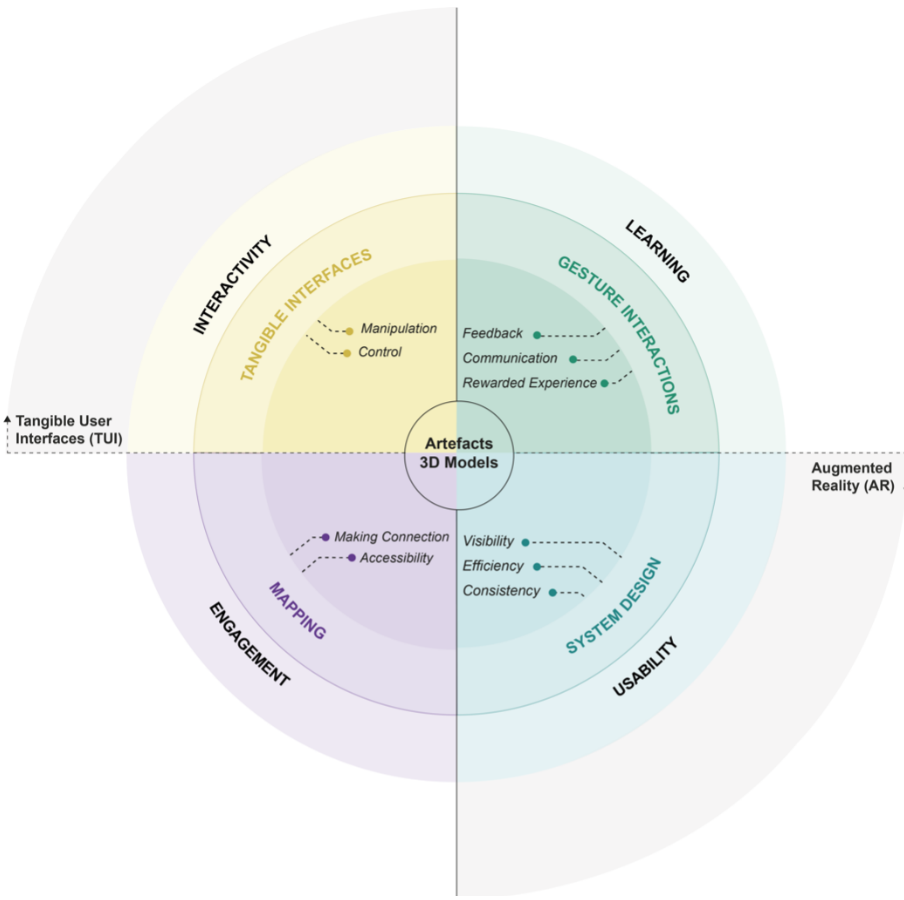

Figure 2: The conceptual framework for developing and evaluating tangible AR interfaces for historical artefacts with the four core themes: Interactivity, Learning, Engagement, Usability, and the four main concepts: Tangible Interfaces, Gesture Interactions, Mapping, System Design, and 10 key aspects: *Manipulation, Control, Feedback, Communication, Rewarded Experience, Making Connection, Accessibility, Visibility, Efficiency, Consistency*.

The four core themes are Interactivity, Learning, Engagement, Usability. The core themes were also analysed in relation to each other and with a connection to the overall data interpretation. Each core theme comprises one of the main concepts. The four main concepts are: Tangible Interfaces, Gesture Interactions, Mapping, System Design. The main concepts are aligned to 10 key aspects: *Manipulation, Control, Feedback, Communication, Rewarded Experience, Making Connection, Accessibility, Visibility, Efficiency, Consistency*.

Table 1. The main concepts aligned with the key aspects and their design characteristics.

Tangible Interfaces		**Mapping**	
Key Aspect	**Design Characteristic**	**Key Aspect**	**Design Characteristic**
Manipulation	Assigning Coherent manipulation for the virtual 3D models in the real-world environment.	*Making Connection*	Aligning virtual 3D models to merge correctly with the generic proxies.
Control	Controlling the generic proxies to view the virtual 3D models from different angles.	*Accessibility*	Creating high-quality scans of original artefacts which allow close inspection of artefacts fine details.
Gesture Interactions		**System Design**	
Key Aspect	**Design Characteristic**	**Key Aspect**	**Design Characteristic**
Feedback	Linking AR interaction techniques to output in AR application.	*Visibility*	Designing Clear and visible interface design.
Communication	Organising information (i.e., text, audio).	*Efficiency*	Designing a responsive application through enhanced AR markers detection.
Rewarded Experience	Learning novel AR interaction techniques.	*Consistency*	Designing interface functions with similar tasks across the application.

Interactivity

The first core theme Interactivity refers to the interactive qualities of the exhibit. Interactivity theme is defined in terms of three factors elicited by the tangible AR exhibit; physical interactions, cognitive interactions, as well as social interactions. Physical interactions offer sensory stimulus and are enriched by allowing the visitor to physically manipulate the historical artefacts using generic physical proxies. Cognitive interactions are supported through the exhibit's ability to stimulate interest and provide the visitor with a sense of discovery and fulfilment when exploring the historical artefacts using the augmented reality application, as stated by one of the visitors: *"great experience, close-up view of the artefacts, fascinating"* (V31). And finally, social interactions are encouraged through the visitors' collective presence enabling conversation about the historical artefacts around the exhibit. Interactivity as a core theme comprises the main concept of Tangible Interfaces.

Tangible Interfaces

The main concept of Tangible Interfaces relates to employing physical objects to manipulate historical artefacts. The visitors can physically hold and manipulate virtual representations of historical artefacts using cylinder-shaped generic proxies. The physical objects serve as an intuitive interface to manipulate the historical artefacts as well as interact with interpretation in AR, which removes any physical obstruction between the visitor and the artefacts. The choice of physical objects was considered through early discussions, as well as co-design interviews with the heritage experts to develop an artefact that can overcome current limitations around physical interaction with historical artefacts due to their fragile nature. Consequently, the use of physical objects as an interaction method using generic proxies produced a very positive effect on the visitor interaction experience with the historical artefacts. This concept relates to bodily interactions [16] as the visitor's hands are part of the interactions and their movements translate to input/output through the physical objects. This main concept is aligned to two key aspects: *Manipulation and Control*.

Manipulation

The ability to physically manipulate objects is an important aspect of analysing historical artefacts, it is also suggested that to fully engage with virtual representations of historical artefacts, it is best to interact via tangible manipulation which can promote thinking through things [23]. This key aspect demonstrates how visitors can manipulate digitised historical artefacts and view them from different angles using cylinder-shaped proxies which are based on simple basic primitive shapes. For instance, visitors expressed that by using the cylinder-shaped proxies, they can easily and physically manipulate the virtual 3D models: "tactile, I could feel the object, not just see it" (V79); "brought me closer to the artefacts" (V76).

Control

The cylinder-shaped generic proxies as physical interfaces afforded the visitors to control the historical artefacts by having an interface that they can grab in their hands similar to handling an original artefact, as expressed by the visitors: "I felt I can control the artefacts" (V7); "brilliant to get hands-on with 3D models" (V18). The physical objects promoted an intuitive and seamless interface that requires no extra gear to operate such as Head-mounted displays or VR controllers, enabling the visitors to keep their focus on the objects at hand without having to press any buttons that would distract and interrupt their interactions, for instance, as in the case of using a touch screen interface.

Learning

The second core theme Learning refers to learning as it occurred while visitors manipulated the historical artefacts using the tangible AR exhibit. The visitors expressed that they learned something 'new' and felt that the exhibit enhanced their knowledge about the Bronze Age artefacts, as commented by the visitors: *"you can experience what they used to be like and used for"* (V15); *"educating, very informative and easy to use"* (V57); *"thought-provoking"* (V69); *"a good way to learn interactively"* (V19); *"I really enjoyed finding out what each item was"* (V53). Additionally, visitors anticipated that the exhibit could apply to other domains such as looking at insects, bones, rocks, and a multitude of historical contexts, *"… has a huge benefit to so many walks of life"* (V66). Learning as a core theme comprises the main concept of Gesture Interactions.

Gesture Interactions

The main concept of Gesture Interactions relates to linking the generic proxies with the interaction techniques as output modalities in AR. For instance, the visitor can use three interaction techniques (*Move, Rotate, Flip*) as output modalities in AR (*Zoom, Select, Switch*) to interact with interpretation, such as text, photographs, maps, and audio, as well as switch between different interface modes in the application (Explore mode or Interpret mode). The interaction techniques were considered during early discussions with the heritage experts on how to enhance the visitor's understanding of the artefacts and promote reflections while physically holding the artefact in hand. Therefore, the visitor would use gestures that they would perform when manipulating a real artefact. This main concept relates to using gestures for manipulation [36] to facilitate interaction with historical artefacts. Prior works on gestures research suggest that gestures can give richer interaction modality [32], transform an artefact identity [12], and give an object a new life [44]. This main concept is aligned to three key aspects: *Feedback, Communication, Rewarded Experience*.

Feedback

Feedback is one of the design principles in interaction design, therefore, it constitutes a key indicator of a good user experience. Feedback is achieved by confirming that the user actions are successfully received by the application [46]. The application interface incorporated interface design elements that communicated the results of the visitors' actions such as unlocking interpretations about the historical artefacts using three interaction techniques (Move, Rotate, Flip) as output modalities in AR (Zoom, Select, Switch). Additionally, the visitors stated that the gestures enabled learning, and enabled the artefacts to come to life… "it made the artefacts come to life" (V27); "a good way to learn interactively" (V19). Additionally, the coupling of gestures with tangibles re-enforces learning about the historical artefacts, as research suggests, physical engagement creates involvement and activeness in learning that passive listening or watching does not [39].

Communication

Gestures Interactions are also considered to facilitate communication, which is identified in the literature to improve thinking and the learning process [17]. The interaction techniques as output modalities in AR allowed sharing of interpretive content such as text and audio to relay information about the historical artefacts, enabling the visitors to reflect on their knowledge about the historical artefacts and hence, aid their learning. The visitors commented: "really amazing insight into the bronze age artefacts" (V24); "informative, and more engaging than object in museum display and labels" (V65); "thought-provoking and educational" (V69). Additionally, in collaborative settings, Stanton et al. (2001) suggest that gestures can also be performative, especially when combined with tangibles, as their influence stretches beyond the digital space to include the physical space [17], which allows the visitor to communicate their state or experience to other visitors.

Rewarded Experience

Gesture interactions can enhance the visitor's knowledge about the historical artefacts prompting a rewarded experience. While the exhibit advocates intuitive tangible AR interfaces to manipulate historical artefacts, the interaction techniques (Move, Rotate, Flip) as output modalities in AR still possessed inherently ambiguous design qualities [14], which aid to promote an inquisitive attitude and drive engagement with new experiences, and subsequently, lead to learning [5]. Initially, the visitors were left to explore on their own, offering them the freedom to unpack the interaction techniques and their output modalities in AR (Zoom, Select, Switch), this process promotes a prolonged engagement with the historical artefacts which in turn deepens the experience and aid learning. Prior research also suggests that systems that may be difficult to learn, but are rewarding to use, particularly for their potential to build physical skills through practiced use [32].

Engagement

The third core theme Engagement refers to the tangible AR exhibit promoting a sense of engagement by allowing the visitors to hold and manipulate virtual 3D models of historical artefacts. The visitors described their experience to be entertaining… *"this is fun"* (V37), *"Cool"* (V52), *"Fantastic"* (V56), *"clever, insightful, and engaging*" (V34). As stated by prior research, entertaining exhibits are considered to be engaging [10]. The visitors also expressed that the tangible AR exhibit made the historical artefacts accessible, enabling them to move, rotate, and closely inspect their fine details as if they were handling the original artefacts, prompting a real lifelike experience… *"engaging activity and very interesting to be able to hold and investigate them*" (V36); *"you can see all the cracks and feel you're actually holding, you can look at all bits of it"* (V37). Additionally, mapping of the virtual 3D models to the generic proxies to explore the historical artefacts and the AR interaction techniques to access interpretations using the physical object as an interface deepened the visitors' connection with the historical artefacts and offered a seamless experience. Engagement as a core theme comprises the main concept of Mapping.

Mapping
The main concept of Mapping relates to aligning the physical objects to their virtual counterparts by integrating the 3D models in the virtual environment to merge with the generic proxies in the real-world environment. It is worth noting, that a slight degree of mismatch can occur between the generic proxies and the virtual representations of historical artefacts due to camera tracking of AR markers, however, the visitors haven't reported any inconveniences due to that issue. This main concept is aligned to two key aspects: *Making Connection, Accessibility*.

Making Connection
The visitors stated that they felt more connected with the historical artefacts using the physical objects, as they were able to hold the artefacts in their hands and take their time to inspect the cracks and pattern details and have a full appreciation of the artefacts. For instance, one visitor stated that seeing the same 3D models of the historical artefacts inside a holographic display didn't yield any interest to them, as they weren't able to touch or get closer to explore the artefacts…*"I felt like I was interacting with the real urns"* (V6)*"; very interesting to be able to "hold" and investigate them in a way you wouldn't normally"* (V36); *"brings Archaeology to life"* (V40); *"quite cool to see it in real life and how it looked like"* (V5).

Accessibility
The ability to access and touch historical artefacts remains one of the challenging matters for museum visitors. The visitors were able to access otherwise inaccessible historical artefacts through the use of generic physical proxies. Additionally, placing the AR markers around the cylinder-shaped proxies improved camera tracking of the AR markers and display of the virtual 3D model, and also helped orient the visitor's hands as if they were handling a real artefact. Accessibility was also supported by very high-quality photogrammetry techniques to produce the 3D model scans of the historical artefacts which enhanced their realism as well, where visitors stated: *"you can see all the cracks and feel you're actually holding; you can look at all bits of it"* (V37); *"I can see it from all angles"* (V53).

Usability
The fourth core theme Usability refers to the user interface design. The augmented reality application should possess a responsive interface, with clear and visible instructions. For instance, optimising AR markers features, and graphical patterns enhances camera detection, which allows faster loading of the virtual 3D models, and hence yields a responsive application. Another important criterion is to have a standard and consistent navigation across the application. For instance, similar functions were applied for the three AR interaction techniques whether the visitor is using Explore mode or Interpret mode. Usability as a core theme comprises the main concept of System Design.

System Design
The main concept of System Design relates to user interface solutions that can adhere to interaction design principles and follow usability guidelines to ensure a good user experience for the augmented reality application. This main concept is aligned to three key aspects: *Visibility, Efficiency, Consistency*.

Visibility
This key aspect corresponds to introducing visual elements to the application interface design which can inform the visitor about the interface status after each interaction. For instance, the application interface featured corresponding audio tracks and coloured frames on the screen every time the visitors flip the cylinder-shaped generic proxies to switch between two modes in the application. In this case, the visitor can easily recognise which of the user interface mode (Explore mode / Interpret mode) is presented to them.

Efficiency
This key aspect corresponds to designing a user interface with efficient navigation and quick loading of the application that allows the visitor to complete tasks as easily as possible. For instance, optimising the Vuforia AR markers with high contrast and sharp features can maximise the efficiency of detecting the AR markers which enable the augmented reality

application to instantly display the virtual 3D models as soon as the AR markers are detected by the camera resulting in a very responsive application.

Consistency

This key aspect corresponds to designing a consistent user interface. Consistency entails an application user interface that behaves following the same set of functions to achieve similar tasks across different interactions. The interaction techniques (*Move, Rotate, Flip*) as output modalities in AR (*Zoom, Select, Switch*) have similar tasks in both modes (Explore mode and Interpret mode) in the AR application. The functions of the interaction techniques behave similarly whether the visitors want to explore the artefacts, interact with interpretation, or switch back and forth between two modes.

6 Discussion

The above illustrated conceptual framework aims to provide insights into developing and evaluating tangible AR interfaces, which focus on the manipulation of historical artefacts. The framework put forward a set of design characteristics to implement during the design process and would also be beneficial when working in smaller museums with fewer resources and experienced teams by providing a formalised approach to conceptualise tangible AR interfaces for historical artefacts. Toolkits and frameworks are well explored in HCI in various capacities such to reduce time and complexity, promote efficiency for replicating ideas and systems [29], and more recently in cultural heritage to empower new audiences to author solutions [37]. The in-situ study analysis enabled the final validation of the framework through the practical implementation of a tangible AR exhibit, serving as a real-world case study for a museum. The next section discusses a series of observations and reflections from the in situ study related to the proposed conceptual framework.

Developing Interactions with Fewer Constraints

The use of physical objects triggered positive reactions, by delivering unique and seamless interactions as expressed by the visitors during the in situ study… *"I felt I had a new experience"* (V23). By using simple primitive objects as tangible interfaces, the exhibit afforded a walk-up-and-use approach, while still possessing ambiguous qualities that triggered the visitors' curiosity to step in, pick one of the cylinder-shaped generic proxies and manipulate it from different angles conveying a sense of control over the artefact. This would suggest that designers and researchers can explore physical objects as tangible interfaces to leverage human motor skills for interaction with historical artefacts and remove physical barriers in museums by developing interactions with fewer constraints [26].

Supporting Learning through Gesture Interactions

The visitors' responses revealed that the exhibit elicited learning by being able to interact with interpretation using the physical objects, for instance bringing the generic proxies closer for listening to audio narration. The key aspects associated with Gesture Interactions (*Feedback, Communication, Rewarded Experience*) were also part of the early discussions with heritage experts on how holding physical objects while hearing the interpretation can enhance the visitors' understanding of historical artefacts. This would suggest that developing tangible AR interfaces for historical artefacts can apply gesture interactions as interaction techniques to promote an active thinking process and support learning about historical artefacts. Additionally, prior works suggest that tangible systems with less constraining interaction styles (i.e., such as having the user's hands stuck on the keyboard or touch screen) are more likely to foster thinking and communication, while consistently assigning physical movement to interface functions can also support kinesthetic learning [24]. Designers and researchers can consider incorporating additional functions for the interaction techniques to fit a specific cultural context. This suggests that the framework can offer designers and researchers of tangible AR interfaces the possibility to expand on the current framework infrastructure to incorporate it with existing standards [35].

Conveying Access to Historical Artefacts

The visitors stated that they were able to feel connected and have access to otherwise inaccessible artefacts by manipulating the generic proxies to examine cracks and view the artefacts' details from all angles. The key aspects associated with the main concept of Mapping (*Making Connection, Accessibility*) also demonstrated that incorporating high-quality scans of the 3D model in the virtual environment improved the perception of historical artefacts and therefore prompts a realistic experience. Designers and researchers can expand the possibilities of mapping between physical objects and virtual representations by altering the artefacts' conditions, for instance, artefacts can be represented as old and found in the ground, perceived as new shiny objects, or while they are in use. Mapping can also be used to convey the artefact's intangible values, such as their material composition and their utility.

7 limitations and future work

The tangible AR exhibit was evaluated in situ for two weeks in an exhibit at a museum. The in-situ study was conducted during the COVID-19 pandemic which meant that the number of visitors is lower than pre-pandemic. Therefore, a longer in-situ study supported by no COVID restrictive measures would yield a larger number of visitors enabling the tangible AR exhibit to be experienced by thousands of visitors and generating greater data on the use of tangible AR to manipulate historical artefacts. Additionally, a longitudinal study would then enhance the possibilities to promote the generalisability of the generic proxies as physical interfaces to manipulate historical artefacts. The conceptual framework discusses keys aspects and design characteristics pertaining to the use of tangible interfaces (generic proxies) to manipulate virtual 3D models of historical artefacts; therefore, it is important to note that the framework aims to help designers, researchers, and cultural heritage professionals in better understanding the design process for developing and evaluating tangible AR interfaces to manipulate historical artefacts, and to be taken as proposed guidelines rather than a prescribed formula.

Furthermore, the in-situ study findings also revealed that the exhibit premise is not limited to just handling historical artefacts, and visitors suggested other application opportunities to other domains that involve tactile feedback, such as prototyping, architectural models, medical fields, wildlife, etc. In future iterations, virtual 3D models could be replaced with any 3D models, offering greater potential to interact with larger virtual assets. Consequently, the conceptual framework can be used in new contexts leading to the development of further concepts and key aspects. In that regard, I also believe it is worth examining how the conceptual framework can be utilised to develop tangible AR interfaces that explore domains requiring some form of tangibility.

8 conclusion

This paper presented a conceptual framework that draws upon relevant literature in HCI to support the conceptualisation of key aspects to formalise the design process for developing and evaluating tangible AR interfaces to manipulate historical artefacts. The framework is evaluated and refined by analysing data from an in-situ study of a tangible AR exhibit at a museum. The study findings have demonstrated that the proposed conceptual framework's main concepts; tangible interfaces, gesture interactions, Mapping, and System Design have supported interactivity, learning, and engagement, as well as can adhere to usability standards for interaction design. Additionally, the study also demonstrated the possibilities of the framework beyond theoretical framing through a real-world case study at the museum, where a tangible AR exhibit offered museum visitors an intuitive and seamless experience that wouldn't be possible using a touchscreen or by looking through traditional museum glass displays.

The conceptual framework encompasses four core themes, Interactivity, Learning, Engagement, Usability, and four main concepts, Tangible Interfaces, Gesture Interactions, Mapping, System Design. Furthermore, the four main concepts are aligned to 10 key aspects: *Manipulation, Control, Feedback, Communication, Rewarded Experience, Making Connection, Accessibility, Visibility, Efficiency, Consistency*, which are transformed into design characteristics to support developing and evaluating tangible AR interfaces to manipulate historical artefacts.

The conceptual framework can serve as a guideline for museums including cultural heritage professionals, researchers, and designers who aspire to build engaging tangible AR exhibits that utilise 3D models of historical artefacts to enhance the visitors' interaction experience and facilitate learning about historical artefacts. Finally, the conceptual framework holds significance through its benefits to provide a set of design characteristics pertinent to designing for new technologies such as Augmented Reality (AR), aiding individuals involved in the development of tangible AR exhibits to adhere to a more straightforward process, while maintaining an efficient timeline.

ACKNOWLEDGMENTS

The author would like to thank Northumberland National Park Authority for their support, the staff for helping and facilitating the exhibit installation, and the visitors for their engagement with the exhibit and taking part in the study.

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