Phygital Heritage: Communicating Built Heritage Information through the Integration of Digital Technology into Physical Reality

KU LEUVEN

ARENBERG DOCTORAL SCHOOL

FACULTY OF ENGINEERING SCIENCE

Phygital Heritage

Communicating Built Heritage Information through the Integration of Digital Technology into Physical Reality

Eslam Nofal

Supervisor:
Prof. dr. Andrew Vande Moere

Co-supervisor:
Prof. dr. Rabee M. Reffat

Thesis presented in partial fulfilment of the requirements for the degree of Doctor of Engineering Science (PhD): Architecture

June 2019

Phygital Heritage

Communicating Built Heritage Information through the Integration of Digital Technology into Physical Reality

Eslam Nofal

Examination Committee:

Prof. dr. Joseph Vandewalle (KU Leuven, Belgium), *chair - preliminary defense*
Prof. dr. Krista De Jonge (KU Leuven, Belgium), *chair - public defense*

Prof. dr. Andrew Vande Moere (KU Leuven, Belgium), *supervisor*
Prof. dr. Rabee M. Reffat (Assiut University, Egypt), *co-supervisor*

Prof. dr. Koenraad Van Balen (KU Leuven, Belgium), *secretary*
Prof. dr. Kris Luyten (UHasselt, Belgium)
Prof. dr. Arnold Vermeeren (TU Delft, Netherlands)
Dr. Vanessa Boschloos (UGent, Belgium)

Abstract

Built heritage forms a unique asset by expressing the richness and diversity of our history, possessing vast amounts of information that varies from factual and explicit, to more tacit and embedded. Tacit knowledge of built heritage is typically more challenging to communicate to visitors in understandable and engaging ways due to its implicit and abstract character. Therefore, we investigate how built heritage information can be disclosed via simultaneous and integrated physical and digital means, and how this information can be communicated to visitors in more engaging, educational and meaningful ways. In this thesis we present the approach of *"Phygital Heritage*", which entails how heritage information can be disclosed via simultaneous and integrated physical and digital means. We hypothesize that this approach forms a potential medium for more engaging and meaningful communication of heritage information to a broader public. It even enables heritage visitors to appreciate heritage in more experiential ways, and to raise community awareness about heritage assets.

Through a set of in-the-wild studies, in which interactive phygital prototypes were designed and deployed in real-world heritage and museum environments, we explore how the seamless integration of digital technology into physical reality facilitates the communication of built heritage information to museum visitors and how it affects user engagement.

- In *Saqqara Entrance Colonnade,* through a between-group comparative study in a real-world museum context, we examined how the tangible characteristics of an interactive museum prototype influence how visitors understand tacit knowledge of built heritage;
- In *Nimrud Relief*, through a field study in a real-world museum environment, we investigated how an augmented reality experience impacts the architectural contextualization of an isolated artifact from the Nimrud palace in Iraq;
- In *Graethem Chapel*, through an in-the-wild study, we investigated how an in-situ interactive projection mapping enables the communication of the spatiotemporal transformation of a medieval chapel that occurred during the last 850 years; and
- In *Neferirtenef Tomb-Chapel*, through a field study in a real-world museum environment, we investigated how a tangible gamification installation supports informal cultural learning of young museum visitors and how it encourages collaboration among them.

In summary, this thesis contributes to the knowledge about the communication of built heritage information by demonstrating how this information can be disclosed via simultaneous and integrated physical and digital means, enabling the broader public to appreciate heritage in more experiential ways.

Samenvatting

De unieke kwaliteiten van gebouwd erfgoed zijn dat het de rijkdom en diversiteit van ons verleden kan weerspiegelen en een enorme rijkheid aan informatie kan bevatten. Deze informatie kan variëren van feitelijke en expliciete gegevens, tot impliciete betekenissen. Voornamelijk deze impliciete informatie op een toegankelijke en engagerende wijze overbrengen is complex omwille van het abstracte en onuitgesproken karakter van deze kennis. In deze thesis presenteren we een *"Phygital Heritage"* aanpak, wat inhoud dat fysieke en digitale middelen geïntegreerd worden om informatie over gebouwd erfgoed te communiceren. We onderzoeken hoe deze benadering kan ingezet worden om een breed publiek op een educatieve en engagerende manier te informeren, om de ervaring van erfgoed te verrijken en bewustzijn te verhogen in de gemeenschap.

In een reeks *in-the-wild* studies werden interactieve *phygital* prototypes ontworpen en ingezet in reeële erfgoed en museum omgevingen. Deze studies verkennen hoe de naadloze integratie van digitale technologie in de fysieke realiteit de communicatie van informatie over gebouwd erfgoed kan faciliteren en hoe dit de gebruikerservaring beïnvloed.

- In *Saqqara Entrance Colonnade* gebruikten we een verglijkende studie tussen groepen om te onderzoeken hoe de fysiek tastbare karaktrisitieken van een interactieve museum installatie het overbrengen van impliciete informatie aan bezoekers beïnvloedt;
- In *Nimrud Relief* onderzochten we hoe een *augmented reality* ervaring een artefact dat verwijderd werd uit zijn originele omgeving (het Nimrud paleis in Irak) toch architecturaal kan gecontextualiseerd worden;
- In *Graethem Chapel* bestudeerden we hoe een gesitueerde, interactieve *projection mapping* het mogelijk maakt om de ruimtelijke transformaties van een Middeleeuwse kapel over de voorbije 850 jaar te communiceren.
- In *Neferirtenef Tomb-Chapel* onderzochten we hoe een fysiek tastbare installatie jonge museumbezoekers ondersteunt in het leren over informele culturel aspecten door middel van *gamification*, en hoe dit kan aansporen tot samenwerken.

Samengevat draagt deze thesis bij aan onderzoek over de communicatie van informatie over gebouwd erfgoed door te demostreren hoe deze informatie kan overgebracht worden via de combinatie van fysieke en digitale middelen, en hoe dit een breed publiek in staat kan stellen om erfgoed op een rijkere manier te ervaren.

Acknowledgements

I am deeply indebted to many people for the roles they played in guiding and helping me to produce this PhD thesis. First, I would like to express my sincere gratitude to my supervisor *Prof. Andrew Vande Moere* for guiding me through this PhD journey. I am grateful to him for his methodological insights, critical reviews, continued support of my endeavors, and encouragement when the going got tough. I am very grateful to my co-supervisor *Prof. Rabee M. Reffat* for his endless support, his continuous and constructive feedback, and his personal and professional advice. Under his academic supervision at Assiut University, the bedrock of this research was set.

I wish to thank the members of my supervisory committee: *Prof. Krista de Jonge* for her comprehensive feedback and advice, and for taking over the role of chairing the committee at the public defense; *Prof. Kris Luyten* for his meaningful input and feedback, and for hosting me among his research group in the early phase of the study presented in Chapter 6; and *Dr. Vanessa Boschloos* for facilitating the museum experiments and for her support throughout the duration of this research. I would like also to thank the external members of the examination committee: *Prof. Koen Van Balen* and *Prof. Arnold Vermeeren* for their interest in my work and for their critical thoughts and suggestions for improvements in the last phase of the PhD.

I would like to thank *Prof. Ann Heylighen* for her motivating feedback from the early phase of this PhD and for hosting me among her team when my foot was broken in spring 2017. A heartfelt thanks to all my colleagues of Research[x]Design for having welcomed me as a part of the family, and for providing practical tips and academic advice. I am very grateful to my former colleagues; *Sandy Claes*, *Niels Wouters*, *Alvin Chua*, and *Thomas Laureyssens* for their continuous help and support, even remotely from around the globe. I would like also to thank my current colleagues; *Jorgos Coenen*, *Georgia Panagiotidou*, *Iremnur Tokac*, *Dieter Michielsen*, *Alex Nguyen* and *Daan Wampers* for being always ready to help and for providing opportunities for collaboration. I wish also to thank the former Master students and interns, who provided help to this work; *Ahmed Elhanafi*, *Robin Stevens*, *Maarten Houben*, *Sinem Görücü*, and *Payam Norouzi*. In general, I would like to thank all my colleagues at the Department of Architecture, who provided inspiration, help and support over lunches, chats and coffee breaks.

I would like to thank *Dr. Hendrik Hameeuw* for opening the doors to collaborate with the Royal Museums of Art and History in Brussels. I owe too much to him for his active collaboration during the course of this PhD. I would like to thank also the Antiquity Department of the museum; *Dr. Luc Delvaux*, *Dr. Bruno Overlaet*, *Dr. Eric Gubel*, and *Bieke Janssens* for their support and assistance during the several museum experiments. Special thanks goes to all the museum visitors who voluntarily participated during their museum visits in the several studies presented in this PhD.

I am grateful to the several facilities of KU Leuven such as FabLab, Limel, and Agora for providing the different materials and equipment needed for this PhD. Moreover, I owe huge gratitude to the International Muslim Student Association in Leuven (IMSAL), and to the Egyptian community in Leuven, for welcoming me from the first day as part of the family, for destroying any cultural and religious barriers that I could have faced, and for providing continuous help and support.

I gratefully acknowledge the PhD scholarship funded by the Egyptian Ministry of Higher Education. I would like also to thank the Egyptian Cultural Bureau in Paris for managing this scholarship.

At last but not least, I am greatly indebted to my family. I wish to express my sincerest gratitude to my dearest wife *Yosr Elghazouly*, who was always and graciously standing by my side, and willingly picked up extra duties with no complaint. She did not only provide emotional and personal support, but also the design of the prototypes in this thesis benefited a lot from her insightful comments, creative thoughts, and programing skills. Likewise, my sweetheart daughter *Sarah* and my darling son *Aser* deserve special thanks for their encouragement and motivation that made me stronger, better and more fulfilled than I could have ever imagined. They joyfully kept helping me in prototyping when tasks transferred to home for so many times. It is difficult to explain how much I owe to these people. None of this work would be possible without their encouragement and patience. Special thanks also goes to my family in Egypt; to my beloved mother and my siblings for the continuous prayer and support they have given throughout this PhD journey; and to the loving memory of my dear father *Prof. Mahmoud Nofal*, who had laid the foundation by teaching me the principles, values and hard work discipline that have served me well in all aspects of life. My Lord, bestow your mercy on my parents, as they cherished me in my childhood.

Above all, all praise and thanks are due to the Almighty Allah who always guides me to the right path and has helped me to complete this thesis with His mercifulness and blessings.

Contents

List of Figures

List of Tables

Chapter 1: Introduction

1

This chapter presents a brief prologue; it introduces the motivations, research problem, and research questions. It concludes with a brief overview of the chapters that follow.

1.1. Setting the Scene

Heritage forms the evidence of the fruitfulness and diversity of our past. Built heritage is an important part of the cultural heritage of towns and cities, as it expresses the richness and diversity of our common past. Current definitions of built heritage are narrow and rely on conventional conceptions of architectural and historical values [Tweed and Sutherland, 2007]. However, built heritage extends to embrace well a diverse collection of tangible (e.g. form and design, materials and substance, location and setting) and intangible (e.g. use and function, traditions and techniques, spirit and feeling) aspects [Van Balen, 2008]. Built heritage should therefore not be interpreted just as physical constructions, but as tangible artefacts that represent meanings and values that might even change over time. Built heritage therefore can be interpreted as a communication process [Kepczynska-Walczak and Walczak, 2015], in which the different types of values and meanings can be perceived, understood and appreciated by a wide range of visitors. Typical values and meanings that originate from built heritage include factual and explicit meanings, which are relatively easy to be graphically represented via text or images. Yet more tacit meanings and values, such as the skills, ideas and experiences that heritage represents, are more challenging to be communicated to the public due to their implicit and often abstract character. Such tacit knowledge is particularly important to understand the complexity and richness of heritage as an experiential and communal concept that is not necessarily declarative or definitive.

In particular, our research focuses on how tacit knowledge of built heritage can be communicated to heritage visitors. We are motivated by the emerging concept of heritage democratization [Rodéhn, 2015], which states how communication forms a crucial matter in heritage, as an exceptional vehicle for spreading knowledge and heritage values by collectively facilitating access and awareness for extended protection [Chiapparini, 2012]. By democratizing its communication beyond heritage professionals for conservation decisions [Fredheim and Khalaf, 2016], the significance of heritage knowledge can be appreciated by a broader public such as to raise community awareness or to enable heritage visitors to appreciate heritage in more experiential ways [Calvi and Vermeeren, 2015].

Most typical forms of heritage communication occur via conventional means, such as written labels or audio guides in museums. Yet following the rapid advancements offered by emerging technologies, heritage information is increasingly represented via more dynamic and interactive formats [King et al, 2016]. These technologies vary in terms of their modality, immersion and integration into the physical manifestation of the heritage environment, including websites, smart phone applications or virtual and augmented reality worlds. In addition, recent developments like the Internet of Things (IoT) [Vongsingthong and Smanchat, 2014] demonstrate how digital technologies are now becoming deeper integrated within the fabric of our physical reality. As such, it is claimed that computers and internet will no longer be only about media and content, but also become invisible [Norman, 1998] and in tandem with real-world physical assets as networked objects able to exchange information, interact with each other as well as with people.

Immersive technologies such as virtual and augmented reality facilitate the communication of heritage information, offering meaningful relationships between heritage artifacts, visitors and context [Reffat and Nofal, 2013]. Augmented Reality (AR) technology allows for superimposed information or virtual objects as if they coexist in the real world [Azuma et al, 2001]. As such, it enables heritage professionals and museum curators to visualize heritage artifacts and to improve the museum visiting experiences [Mohammed-Amin, 2015; Nofal, 2013]. In contrast to virtual reality, AR enables engagement and communication by breaking the barrier between virtual objects and physical museum artifacts [Li et al, 2012]. Moreover, AR is used for educational purposes in museums in order not only to enhance engagement and motivation, but also to create an informal and novel learning environment by coupling the digital content and the physical reality, incorporating game strategies to enhance the communication and interpretation of historical contents in engaging ways [Chang et al, 2014; Yilmaz, 2016; Angelopoulou et al, 2012]. The communication of heritage information benefits from two distinct techniques of AR within the confines of a physical building itself and in an architectural scale [Ridel et al, 2014]. So-called 'see-through AR' promises to facilitate learning and user engagement in heritage contexts by superimposing virtual objects on the real scene via portable (e.g. smartphones and tablets [Vlahakis et al, 2002]) or wearable devices (e.g. HoloLens [Pollalis et al, 2017]). In turn, 'spatial AR', which is also known as 'projection mapping' [Mine et al, 2012], augments the environment of the user with images or videos that are projected directly on the physical reality [Raskar et al, 1998]. Spatial AR does not require wearable displays or goggles, and is more apt in providing an experience that can be enjoyed by multiple people simultaneously. The situatedness of projection mapping makes it relevant for conveying heritage information in-situ, as the graphical depiction of the information can be directly and physically related to the heritage environment on which the projection occurs [Rekimoto et al, 1998; Nofal et al, 2017.c].

On the other hand, the emerging research field of 'tangible interaction' promises several qualities that enable the communication of the different forms of heritage information. Tangible Interaction spans a variety of perspectives, such as Human-Computer Interaction (HCI) and Interaction Design, but specializes on interfaces or systems that are in some way physically embodied. Broadly, Tangible Interaction encompasses user interfaces and interaction approaches that emphasize [Hornecker, 2016]: tangibility and materiality of the interface, physical embodiment of data, and embeddedness in real spaces and contexts.

The qualities of built heritage and museum environment (such as original physical artifacts, real scale, texture, visible history, and sharing the space among visitors), allow for designing and deploying tangible user interfaces (TUIs) in order to embrace the physical materialities of artifacts in the visiting experience [Dudley, 2010]. TUIs are believed to be more collaborative, attract more visitors, and persuade them to explore further. TUIs tend to communicate meaning through their physical affordances [Macaranas et al, 2012], such as by mapping information into physical shapes and forms, or material attributes (e.g., size, shape, texture, color, weight). Further, the embedded representation of information by giving the data physical form and blending it with physical environment is believed to be the most useful at human-accessible scales, where the physical size maximizes visibility and reachability [Willett et al, 2017].

Moreover, TUIs possess several qualities that might well facilitate heritage communication, such as requiring little experience or skills, and performing better in terms of recalling information because it requires multimodal ways of human perception to discover and decipher their meaning [Seo et al, 2015]. TUIs also support collaborative and participative processes among users [Claes and Vande Moere, 2015; Not et al, 2019], and attract more visitors towards more extensive forms of exploration during interactive exhibits [Ma et al, 2015]. Tangible interaction has already been scientifically investigated as a potential means to communicate different forms of heritage information, such as the use of 3D printed replicas of original artifacts to trigger digital narrative content [Rapetti, 2005; Marshall et al, 2016]. Further, the tactile qualities of tangible interaction allow for interactive installations in museums that target specific audience [Duranti, 2017]. For instance, the mix of materialities encourages creativity for playful exploration and allows for educational opportunities in a children's exhibition [Taylor et al, 2015].

Based on these emerging technological movements, we propose a potential communication medium that enables the exploitation of typical advantages of both digital and physical reality. We believe that the field of built heritage forms an ideal application domain to exploit the seamless integration of both the digital and the physical (i.e. *phygital*) in order to communicate heritage information in more engaging, educational and meaningful ways. Accordingly, we coin the term ***"Phygital Heritage"*** that entails how heritage information can be disclosed via simultaneous and integrated physical and digital means. We characterize phygital heritage based on: (a) the level of physical affordance, such as how the features of an interface physically support or facilitate taking an action; and (b) the level of situatedness, such as how far the technology is integrated into the physical reality to communicate information. We believe that the qualities of phygital (i.e. the simultaneous and integrated physical and digital means) enables the broader public to appreciate heritage in more experiential ways. Yet, more knowledge is required to demonstrate how phygital facilitates the communication of built heritage information and how it influences visitors' engagement and fosters social interaction among them.

1.2. Research Approach

The research approach of this PhD thesis extracts knowledge from the field of human-computer interaction (HCI) by developing experimental designs and conducting in-the-wild studies in heritage environments such as museums. The research in this thesis is generally guided by an overarching research question on how *phygital heritage*, the integration of digital technology 'into' physical reality, facilitates the communication of built heritage, which includes tacit knowledge and factual information.

1.2.1. Research Questions

The fundamental hypothesis of this research is that the approach of phygital heritage has the potential to become an engaging and meaningful communication medium of the tangible and intangible information of built heritage. The main research question that this research aims to address is:

- ***RQ0.* How can *"phygital heritage"*, the integration of digital technology into physical reality, facilitate the communication of built heritage information to museum visitors?**

In order to generate knowledge that solves the specific concerns of built heritage communication, the research question has been dissected into three domains about the goal, indicators, and assessment of phygital heritage. The main goal of phygital heritage is related to communication:

- *RQ1 Communication.* How can phygital experience enhance the communication of built heritage information?

We characterize phygital heritage by three categorical indicators: engagement, situatedness, and physical affordance. One underlying research question is dedicated for each:

- *RQ2 Engagement.* How can phygital experience influence visitors' engagement and foster social interaction in museums and heritage environments?
- *RQ3 Situatedness.* How does the level of situatedness influence the phygital experience of communicating heritage information?
- *RQ4 Physical affordance.* How does the level of physical affordance influence the phygital experience of communicating heritage information?

The last research question is devoted to the assessment process of phygital heritage in museum and heritage environments:

- *RQ5 Evaluation.* How can phygital heritage be evaluated in heritage environments such as museums?

We investigated each of these questions by drawing from several related disciplines (e.g. human-computer interaction, digital heritage, built heritage), and answered the questions in the context of museums and heritage environments through specific studies. The relation between the research questions and these studies is further clarified in Table 1-1.

Table 1-1: Relation between the individual studies of this thesis and the research questions they address.

		Saqqara Entrance Colonnade	*Nimrud Relief*	*Graethem Chapel*	*Neferirtenef Tomb-Chapel*
Goal	**RQ1.** Communication	✓	✓	✓	✓
Indicators	**RQ2.** Engagement	✓	✓	✓	✓
	RQ3. Situatedness		✓	✓	✓
	RQ4. Physical affordance	✓		✓	✓
Assessment	**RQ5.** Evaluation	✓	✓	✓	✓

1.2.2. Research Methodology

Since our research spans the fields of human-computer interaction (HCI), digital heritage, and built heritage, we adopted a research methodology that encompasses design-oriented HCI research [Fallman, 2007], and in-the-wild evaluations [Rogers, 2011]. Each of the four studies conducted in this thesis involves the design and deployment of an approach of phygital heritage to communicate a specific type of heritage knowledge, providing a comprehensive discussion that reveals relevant design recommendations, shortcomings and challenges, and opportunities for future research.

As illustrated in Table 1-2, we designed a TUI to communicate the symbolic significance of *Saqqara Entrance Colonnade*, an AR application to architecturally contextualize the *Nimrud Relief*, an interactive projection mapping to communicate the spatiotemporal transformation of *Graethem Chapel*, and finally a tangible gamification installation to support informal cultural learning of *Neferirtenef Tomb-Chapel*.

Table 1-2: Matrix of the types of knowledge of built heritage and the different phygital approaches that are addressed in the course of this PhD thesis.

		Types of knowledge			
		Symbolic significance	Architectural context	Spatiotemporal transformation	Informal cultural learning
Phygital approaches	Augmented reality application		*Nimrud Relief*		
	Interactive projection mapping			*Graethem Chapel*	
	Tangible user interface	*Saqqara Colonnade*			
	Tangible gamification installation				*Neferirtenef Tomb-Chapel*

1.2.2.1. Design-Oriented HCI Research

We present four studies that integrate design of phygital prototypes. We produce new knowledge by involving typical design activities in the research process, where research is the area and design is the means [Fallman, 2007]. The design encompassed physical components, digital cross-media information and user interfaces. Ultimately, these phygital prototypes were implemented and deployed in real-life settings (i.e. museums and heritage environments). The development of the studies involved several research and design activities, such as literature review, participatory design workshops with heritage professionals, prototyping, and analysis.

1.2.2.2. In-the-Wild Evaluation

Our studies were conducted in museums and heritage environments, focusing on creating and evaluating phygital prototypes in-situ, in order to benefit from high ecological validity [Chamberlain et al, 2012]. All prototypes captured some form of field observations which were analyzed together with the responses of semi-structured interviews and questionnaires.

1.3. Thesis Overview

Table 1-3 presents an overview of the following 6 Chapters of this thesis and their contributions. In Chapter 2, we present the model of phygital heritage as a potential medium for more enriched and engaging communication of heritage meanings and values. Upon the start of this research, little was known on whether and how phygital approach is effective in communicating knowledge or meaning, let alone in the context of revealing tacit knowledge of built heritage. Chapter 3 (*Saqqara Entrance Colonnade*) was therefore set up as an exploratory study to investigate this issue and to benchmark different tangible interaction and feedback modalities through a between-group comparative study in a real-world museum context, thereby focusing on RQ1, RQ2, RQ3, and RQ5 (Figure 1-1.a). The study in Chapter 4 (*Nimrud Relief*) focuses more on the role of architectural context in built heritage communication through the augmented phygital experience (RQ1, RQ3), exploring RQ2 and RQ5 (Figure 1-1.b). The study in Chapter 5 (*Graethem Chapel*) investigates how the phygital experience can be extended in-situ by including a TUI to control an interactive projection mapping for communicating the spatiotemporal transformation of architectural heritage (RQ1, RQ3), with the focus on RQ2, RQ4, and RQ5 (Figure 1-1.c). While Chapter 6 (*Neferirtenef Tomb-Chapel*) introduces the approach of tangible gamification by combining tangible interaction with gamification, as a promising phygital experience that enhances informal cultural learning of built heritage and fosters collaboration and engagement of young museum visitors, thereby focusing on all research questions (RQ1, RQ2, RQ3, RQ4, and RQ5), as in Figure 1-1.d.

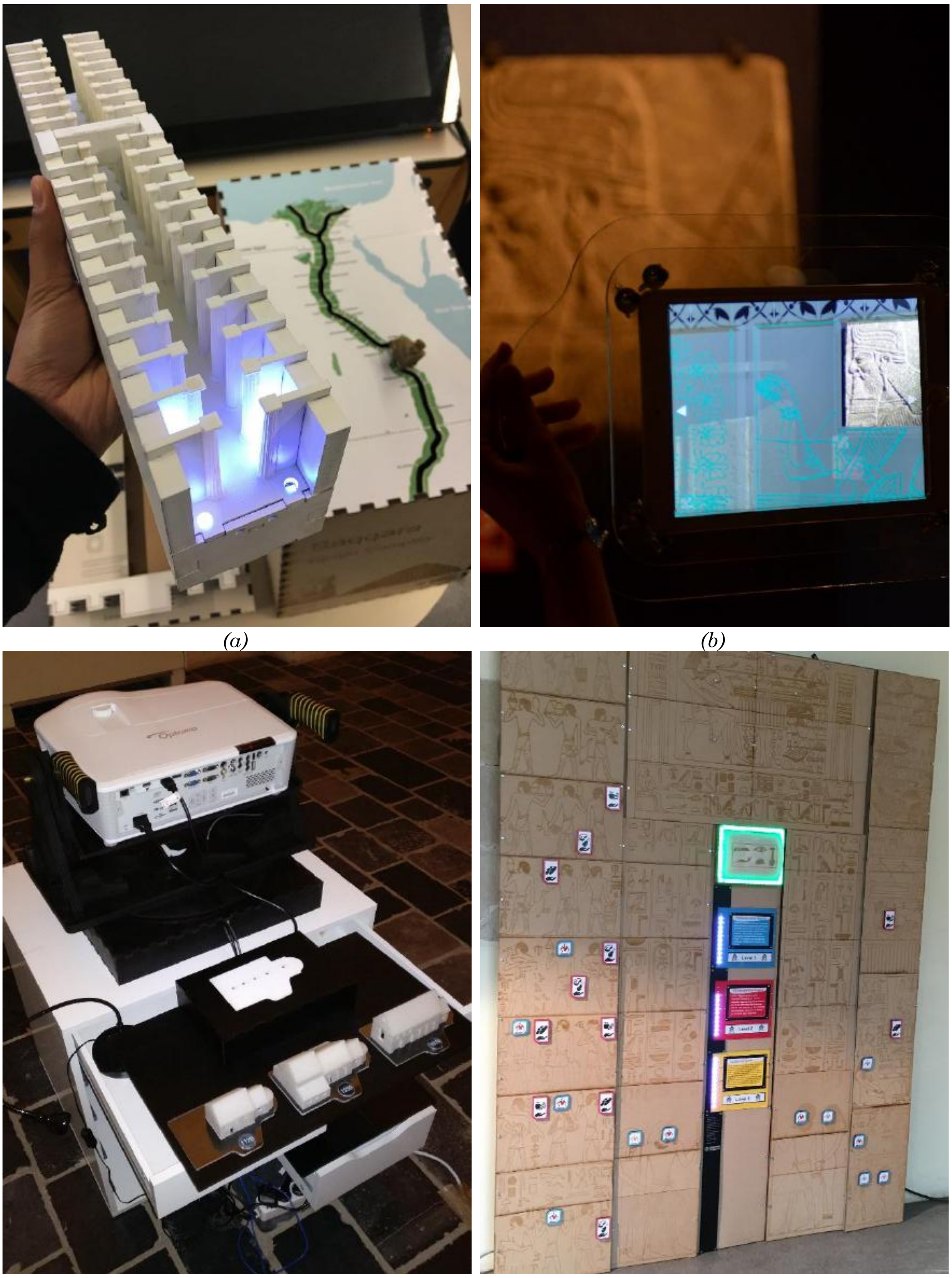
Each Chapter presents the deployment of a phygital prototype (Figure 1-1), and is concluded with a number of design considerations (Table 1-3) for communicating built heritage information. The Chapters are presented in a chronological order as it demonstrates how the model of phygital heritage evolved over the case studies.

Finally, in Chapter 7, we present an amended version of the Phygital Heritage model based on the overall results of the different Chapters. We combine our results and insights into guidelines for communicating heritage through tangible mediums, and present a discussion on the four prototypes that were developed in the course of this research.

The appendices of the thesis include: (a) Appendix I: a position paper that reports on the gap between HCI research in Egypt and Europe due to socio-economic and political contextual factors that might potentially impact the findings on design and evaluation methods of in-the-wild studies, and (b) Appendix II: side studies, in which I report on my participation and role in different international venues related to the fields of digital heritage and museum studies during the course of my PhD research.

Table 1-3: *Overview of the Chapters of this thesis and their contributions*

Chapter	Main Contributions
2. Introduction	• A model of *"Phygital Heritage"*.
3. Saqqara Entrance Colonnade	• Three conditions of a phygital prototype ranging from traditional digital displays to fully tangible means of interaction. • Identification of the relationship between the physical affordance and the required cognitive effort in phygital experiences. • Communicating correct scale through grasping physical models of built heritage. • Identification of the role of material characteristics in heritage communication.
4. Nimrud Relief	• An augmented phygital prototype (AR application). • Identification of the role of context in heritage communication. • Six design recommendations to overcome the AR usability issues in museums. • Novel evaluation methodology to capture visitor's perception and memorability of contextual information such as architectural features.
5. Graethem Chapel	• A phygital prototype encompass a TUI and an interactive projection mapping. • Eight design recommendations for communicating the spatiotemporal transformation of heritage in-situ.
6. Neferirtenef Tomb-Chapel	• A tangible gamification prototype. • Four design recommendation for enhancing the informal cultural learning through the approach of tangible gamification. • Novel evaluation methodology to collect intense data from children in loaded environments.
7. Conclusion	• Amended model of *"Phygital Heritage"*. • A design workflow of phygital heritage. • Four phygital prototypes. • Six design guidelines for supporting heritage communication through phygital mediums. • An evaluation framework of phygital heritage communication.



(a) (b) (c) (d)

Figure 1-1: *The four phygital prototypes presented in this thesis range from (a) a TUI to communicate the symbolic significance of built heritage in Chapter 3, (b) an AR application to communicate the architectural context of heritage in Chapter 4, (c) an interactive projection mapping installation to communicate the spatiotemporal transformation of built heritage in Chapter 5, and (d) a real scale tangible gamification installation to support cultural learning for young museum visitors in Chapter 6.*

1.4. Publications and my Role

The main body of this thesis consists of research that was published in academic peer-reviewed journals (Chapters 3, 4, 5 and 6) or conferences (Chapter 2) over the course of the doctoral research[1]. The publication that is referenced in Chapter 6 has been submitted to ACM Journal on Computing and Cultural Heritage, and is currently under peer review. Each paper discusses research questions, related work, a phygital approach of communicating the information of built heritage to public visitors, and a set of discussion points and design recommendations for future research or potential further development of communicating heritage. Below is a list of the publications included in this thesis and a description of my role in each (Figure 1-2).

Chapter 2

Nofal E.; Reffat R.; Vande Moere A. (2017.c). Phygital heritage: An approach for heritage communication. *The 3rd Annual International Conference of the Immersive Learning Research Network (iLRN2017)*. Coimbra, Portugal, 26-29 June 2017, pp. 220-229, DOI: https://doi.org/10.3217/978-3-85125-530-0-36

At the early phase of my PhD, I proposed to my supervisors (Andrew Vande Moere and Rabee M. Reffat) writing on a conceptual approach for heritage communication to be the outline of my PhD research. They both contributed to the development and the refinement of the model presented in this paper. The publication was authored by myself, with extensive review from Andrew Vande Moere and Rabee M. Reffat.

Chapter 3

Nofal E., Reffat R.; Boschloos V.; Hameeuw H.; Vande Moere A. (2018.a). Evaluating the role of tangible interaction to communicate tacit knowledge of built heritage. *Heritage* 2018, 1(2), 414-436, DOI: https://doi.org/10.3390/heritage1020028

Nofal, E.; Reffat, R.M.; Vande Moere, A. (2017.a). Communicating built heritage information using tangible interaction approach. In Proceedings of the *11th International Conference on Tangible, Embedded, and Embodied Interaction (TEI '17)*, Graduate Student Consortium, Yokohama, Japan, 20-23 March 2017, pp. 689-692, DOI: https://doi.org/10.1145/3024969.3025035

Nofal, E.; Boschloos, V.; Hameeuw, H.; Vande Moere, A. (2016). The role of tangible interaction for communicating qualitative information of built heritage. *Arqueológica 2.0: The 8th International Congress on Archaeology, Computer Graphics, Cultural Heritage and Innovation*, Valencia, Spain, 5-7 September 2016, pp. 441-444.

The study presented in these papers was initiated when I attended in the very early phase of my PhD (March 2015) a Colloquium of "Beyond 3D Digitization: Applications of 3D Technology in Cultural Heritage" as part of the Digital Museum Expo, which was held at the Royal Museum of Art and History in Brussels. There, I met Hendrik Hameeuw, who was working at the museum and proposed the

[1] A complete overview of publications, including those not included in this thesis, can be retrieved from: https://scholar.google.be/citations?user=el_Xq10AAAAJ&hl=en

monumental scale model of the Djoser pyramid complex in Saqqara as a springboard for my PhD research. Together with Andrew Vande Moere, we formulated the research objective and the conceptual design. I designed and fabricated the different installations and executed the observations and interviews in the museum. I carried out the extensive analysis (qualitative and quantitative). The publication was authored by myself with comprehensive review from Andrew Vande Moere, and additional support from co-authors Rabee M. Reffat, Vanessa Boschloos, and Hendrik Hameeuw.

Chapter 4

<ins>Nofal E.</ins>; Elhanafi A.; Hameeuw H.; Vande Moere A. (2018.b). Architectural contextualization of heritage museum artifacts using augmented reality. *Studies in Digital Heritage (SDH)*, 2(1), 42-67, DOI: https://doi.org/10.14434/sdh.v2i1.24500

In this study, I took the lead to network with the Faculty of Media Engineering and Technology, German University in Cairo to host one bachelor student from the department of Computer Science for a period of six months to conduct his bachelor thesis. Thus, I acted as a daily supervisor of Ahmed Elhanafi, who developed the AR application. The case study from the museum was recommended by Hendrik Hameeuw. Together with Ahmed Elhanfi, we executed the observations and interviews in the museum, and carried out the analysis, which I further developed extensively. The publication was authored by myself, with additional support from co-authors Ahmed Elhanfi, Hendrik Hameeuw, and Andrew Vande Moere.

Chapter 5

<ins>Nofal E.</ins>; Stevens R.; Coomans T.; Vande Moere A. (2018.c). Communicating the spatiotemporal transformation of architectural heritage via an in-situ projection mapping installation. *Digital Applications in Archaeology and Cultural Heritage (DAACH)*, 11C (2018) e00083, DOI: https://doi.org/10.1016/j.daach.2018.e00083

This study was based on a Master thesis of Robin Stevens, who I was co-guiding. The case study was recommended by Thomas Coomans to exploit the results of a previous Master thesis. The technical design was done by Robin Stevens with the support of myself and Andrew Vande Moere. I contributed to the evaluation methodology and the qualitative analysis, which I further developed extensively. The publication was authored by myself, with additional support from co-authors Robin Stevens, Thomas Coomans, and Andrew Vande Moere.

Chapter 6

<ins>Nofal E.</ins>; Panagiotidou G.; Reffat R.; Hameeuw H.; Boschloos V.; Vande Moere A. (under review). Situated tangible gamification of heritage for supporting collaborative learning of young museum visitors. *ACM Journal on Computing and Cultural Heritage (JOCCH).*

In this study, I have taken the lead in laying out the research objectives, designing and developing technical components. The case study was recommended by Vanessa Boschloos as she contributed together with Hendrik Hameeuw in defining the goals of cultural learning. Together with Andrew Vande Moere, we set up the conceptual design. I executed the observations and interviews in the museum with the assistance of interns and volunteers. I carried out the extensive qualitative analysis. Georgia Panagiotidou joined the study in the last phase by contributing to the game theory and its ramifications in the paper. The publication was authored by myself, with extensive review from Andrew Vande Moere, and additional support from co-authors Rabee M. Reffat, Georgia Panagiotidou, Vanessa Boschloos, and Hendrik Hameeuw.

Appendix I

Nofal E.; Claes S.; Vande Moere A. (2017.b). From Europe to Egypt: Designing, implementing and evaluating interactive systems in-the-wild. Workshop on Designing for the Arab World, *Designing Interactive Systems (DIS '17)*. Edinburgh, UK, 10-14 June 2017.

I proposed the idea of this paper to Sandy Claes, as I have an Egyptian background, while my PhD study was conducted in a different research environment in Europe. We based this position paper on the differences between those two contexts that might potentially impact the findings on design and evaluation methods of in-the-wild studies. The publication was authored by myself, with additional support from co-authors Sandy Claes, and Andrew Vande Moere.

(a) *(b)*

(c) *(d)*

Figure 1-2: *My role in the different studies: (a) interviewing parents while children were still interacting with the prototype in Chapter 3, (b) inviting museum visitors to participate in the study presented in Chapter 4, (c) contributing to the prototyping process of the study in Chapter 5, and (d) introducing the installation of the study in Chapter 5 to a school visit in the museum.*

Chapter 2: Phygital Heritage

2

This chapter has been previously published as:

Eslam Nofal et al. (2017.c). “Phygital Heritage: an Approach for Heritage Communication”, In Proceedings of the *3rd Annual International Conference of the Immersive Learning Research Network (iLRN2017)*, Coimbra, Portugal, 26-29 June 2017, pp. 220-229, DOI: https://doi.org/10.3217/978-3-85125-530-0-36

Abstract

Physical heritage objects and assets are related to a vast amount of digital information of different kinds, which are challenging to be communicated to visitors in understandable and engaging ways. Yet recent technological advances promise new opportunities to more tightly merge the digital with the physical world. This paper therefore introduces the concept of *“phygital heritage”*, the integration of digital technology ‘into’ physical reality, as a potential medium for more enriched and playful communication of heritage values and qualities. We propose that phygital heritage should enable the exploitation of typical advantages of both digital and physical reality, and that distinct categories of phygital can be recognized based on: 1) the level of physical affordance; and 2) in how far the technology is integrated into the physical reality. The paper also opens the discussion about the potential challenges and concerns which future explorations, scientific research and real-world applications of phygital heritage probably will encounter.

2.1. Introduction to Phygital

Heritage forms the evidence of the fruitfulness and diversity of our past. Accordingly, most heritage artefacts represent a vast amount of information, ranging from simple factual aspects to more complex qualitative, tacit qualities and values. Following the current movement towards the democratization of culture [Gattinger, 2011], there exists a general tendency towards making heritage information more available and accessible to the wide public, such as to make people aware of the value and richness of their and others’ heritage. Heritage information tends also to be communicated to support its deeper understanding, or to engage and even immerse visitors in heritage environments [Rubegni et al, 2010]. Most typical forms of communication occur via conventional means, such as written labels or audio guides in museums. Yet following the rapid advancements offered by modern digital technologies, heritage information is now also increasingly represented via more dynamic and interactive formats, including websites, smart phone applications or virtual and augmented reality worlds. In addition, recent developments like the Internet of Things (IoT) [Vongsingthong and Smanchat, 2014] demonstrate how digital technologies are now becoming deeper integrated within the fabric of our physical reality. As such, it is claimed [Vongsingthong and Smanchat, 2014] that the Internet will no longer be only about people, media and content, but also will include real-world physical assets as networked objects able to exchange information, interact with each other as well as with people. Along with these emerging technological movements, an overarching term *"phygital"* has been proposed [Uspenski, 2013; Teo, 2013; Nakazawa and Tokuda, 2007; Lupetti et al, 2015; Bazzanella et al, 2014] that conceptualizes the blending of the physical and the digital, in so far that they do not simply complement, but rather reinforce each other. Accordingly, the term *"phygital"* was coined [Uspenski, 2013] to denote how everyday objects are connected to their environment, gathering the information and adapting their performance accordingly without human intervention.

The field of marketing has used the term *"phygital"* (e.g. [Teo, 2013]) as a conceptual idea that bridges e-commerce tools to physical stores, often to connect the digital presence of a brand or product to an immersive real-world experience, wherein a digital action can trigger a physical reaction, or vice versa, a physical action can result in a digital reaction. Such endeavor can be typically achieved by making the physical world a type of information system, such as by embedding machine-readable traces or sensors into physical objects so that they are able to communicate to users through digital interfaces [Teo, 2013]. Yet phygital characteristics can also be recognized beyond the field of marketing and retail, with application domains as diverse as education, gaming and tourism. For instance, *phygital map* exploits the physical advantages of paper-based Atlases such as the ease of navigation and the tactile impression of browsing, and merges these with the qualities of digital media, like allowing access to a wide range of audio and video content, which even can be regularly updated [Nakazawa and Tokuda, 2007]. Similarly, *phygital game* adds a physical experience to a compelling digital game in order to reduce the necessary screen time in favor of more healthy forms of physical engagement [Lupetti et al, 2015], hereby allowing the embodiment of the user into a robot as the manifestation of the virtual into the physical. The idea behind phygital can even be deployed as a participative method, as the project *phygital public space* demonstrates how citizen engagement can be fostered via digital blogs for easily sharing and shaping their public space by stimulating interaction between the participants, gathering information and reporting the analogic data on a shareable bases [Bazzanella et al, 2014]. Here, the project also merges physical onsite workshops and analyses such as sound and visibility surveys to capture the flow map of pedestrian's movement in the public space, and merges all this data into a phygital experience.

2.2. Phygital Heritage Model

Based on these theoretical and practical manifestations, we propose *"Phygital Heritage"* as a potential future research subfield, which entails how heritage information can be disclosed via simultaneous and integrated physical and digital means. By blending the digital empowerment of cultural learning, storytelling and entertainment into the heritage artefact, activity or environment, heritage forms an ideal application field to give meaning to the digital experience, and in turn, the digital medium is able to truly provide immediate access to the dynamic relevant resources.

Several related domains have already demonstrated the value of the physical in human-computer interfaces. For instance, in comparison to traditional graphical user interfaces (GUIs), tangible user interfaces (TUIs) are perceived to be more compelling and intuitive to use. TUIs do not only afford objects in an abstract physical form, but they also allow the incorporation of material attributes (e.g. size, shape, texture, color, weight) in order to convey information [Macaranas et al, 2012]. Well-considered TUIs can also provide lay users with more intuitive affordances that steer digital actions, as physical objects tend to be more familiar, approachable, and less abstract to use than traditional digital interfaces [Claes et al, 2015.a]. As such, heritage communication has already benefited from recent TUI advances. For instance, tangible smart replicas have been used in museum exhibitions to provide an additional layer (narrative content) of storytelling on top of factual information presented on text labels, typically located next to the original heritage objects [Marshall et al, 2016]. Furthermore, anecdotal evidence shows that the touch and manipulation affordances of TUIs in interactive exhibits tend to attract more visitors, even persuade them to explore further and deeper [Ma et al, 2015]. Tangible installations can also be deployed in outdoor heritage environments where lack of power supplies or digital networks can exist. For example, the interactive belt [Petrelli et al, 2014] supports the visit of archaeological sites by enabling visitors to select the story they want to listen to and to be part of it, triggering by specific points of interests. Another example is the utilization of a monument of urban space 'City Mouse' as a tangible user interface [Häkkilä et al, 2014], a landmark of a large stone sphere representing the globe, which people could push to a rolling motion in order to rotate a 3D image of the Earth that is visualized on a screen next to the landmark.

These examples, among others, demonstrate how the combination of physical and digital is still relatively unexplored, but potentially particularly valuable for the field of heritage communication, such as when the digitally augmented experience makes some sort of meaningful connection to the actual heritage context, such as the social, cultural and physical characteristics of the physical reality.

Mixed reality is defined as "…anywhere between the extrema of the virtuality continuum" [Milgram and Kishino, 1994], a continuum that extends from the completely real through to the completely virtual environment, with augmented reality and augmented virtuality taking on positions in-between. However, mixed reality relies more on displays and screens, a medium that a relatively contextless and lacks material qualities. On the other hand, we believe that phygital focuses on exploiting material-driven affordances, where the medium does not only conveys visual but also tactile qualities, in addition to physical affordance and playfulness. In the future, phygital heritage can thus be grounded on the combination of the key characteristics of both digital and physical realms for the goals of communicating and interacting with digital as well as physical present heritage information. Relevant key qualities of the digital medium include, but are not limited to:

- *Providing access to rich and vast forms of information.* Heritage information originates from multitude of sources, and is manifested in many different forms, encompassing a vast amount of content that could potentially be disseminated. Regardless of the size, dimensionality or time-dependency of this data, digital technology allows for its immediate access through many different output media. For instance, a phygital interface is capable to convey distinct layers of information related to a heritage object depending on the actual communication medium, ranging from traditional displays to portable or wearable AR technology [Vlahakis et al, 2002].

- *Personalization of information.* Digital information can be offered or automatically filtered according to the profile of visitors, including their age or personal interests [Reffat and Nofal, 2013]. In addition, heritage experts can also specify the types, quantity or interpretation of content according to the surrounding context [Petrelli et al, 2013] or other kinds of dynamic constrains.
- *Information immersion.* Digital display technology allows users to become immersed in the information, stimulating several senses (e.g. audio, tactile, touch) simultaneously in order to provide a more believable or tacit experience that better contextualizes the intrinsic values of heritage. For instance, virtual reality technology now enables users to navigate within stimulated 3D worlds that resemble the original heritage situation, in so far that it has been shown that such environments are more effective in supporting learning activities [Chen et al, 2013].

In turn, the phygital features combine the key characteristics of the physical realm that include, but are not limited to:

- *Physical affordance,* which denotes how the physical form demonstrates the possibility of an action on an object or the environment to people. As such, tangible interfaces are capable to make use of people's experience of interacting with real world objects [Hurtienne et al, 2007]. As such, evidence from educational psychology shows that the manipulation of physical representations of information and utilization of TUIs facilitate understanding [Jansen et al, 2015]. The physical properties of heritage artefacts may thus invoke visitors' pre-existing knowledge to discover their meaning, functionality or use, and consequently lead to more intuitive or memorable forms of communication. Accordingly, phygital interfaces might thus allow users to not only touch heritage artefacts (or their replicas), providing not only the subjective experience of its shape, materiality or weight, but also for a tactile exploration of its potential use.
- *Physicalization.* Information has already been visualized in physical manners for thousands of years, ranging from measuring instruments, passive visualizations, to more interactive forms of visualizations [Dragicevic and Jansen, 2012]. For abstract information, which lacks tangible counterparts (e.g. numbers, networks), its encoding into physical form (physicalization) still improves the efficiency of information retrieval, particularly when it can be freely touched [Jansen et al, 2013]. Similar physical qualities of heritage objects can be conveyed via haptic devices like "open drawer" displays, allowing visitors to reveal parts of an exhibit [Petrelli et al, 2013].
- *Situatedness.* Situated communication depends on how the information relies on the "physical context" to be understood [Rekimoto et al, 1998]. Varying degrees of situatedness exist, ranging from non-situated objects which are typically shown on museum walls or displays and thus require textual labels or legends to be

understood, to fully situated objects like ruins and statues, of which the value can only be comprehended by experiencing and interpreting the surrounding context. Notably, most websites and virtual reality applications are non-situated in nature, allowing users to appreciate heritage regardless of their location yet lacking tacit and intangible qualities. Most projection mappings are more situated, as the graphical depiction of the information can be directly and physically related to the artefact on which the projection occurs.

The aforementioned characteristics have been combined in our proposed model *"phygital heritage"*, shown in Figure 2-1. The model captures the most relevant technologies that are relevant to the integration of digital technology into physical objects in the context of cultural heritage. Such forms of integration range from separated entities that are added 'on top of' physical reality (e.g. augmented reality), to its seamless and invisible embedment (e.g. shape-changing interfaces). The horizontal axis represents the level of physical affordance, such as how the features of an interface physically support or facilitate taking an action. The vertical axis conveys the level of situatedness, or how the technology depends on the physical context to communicate information. The model considers that almost every communication technology is *phygital* in some way or form, but some are more phygital than others. Accordingly, the model proposes three distinct categories of phygital heritage; augmented (P1), integrated (P2), and actuated (P3).

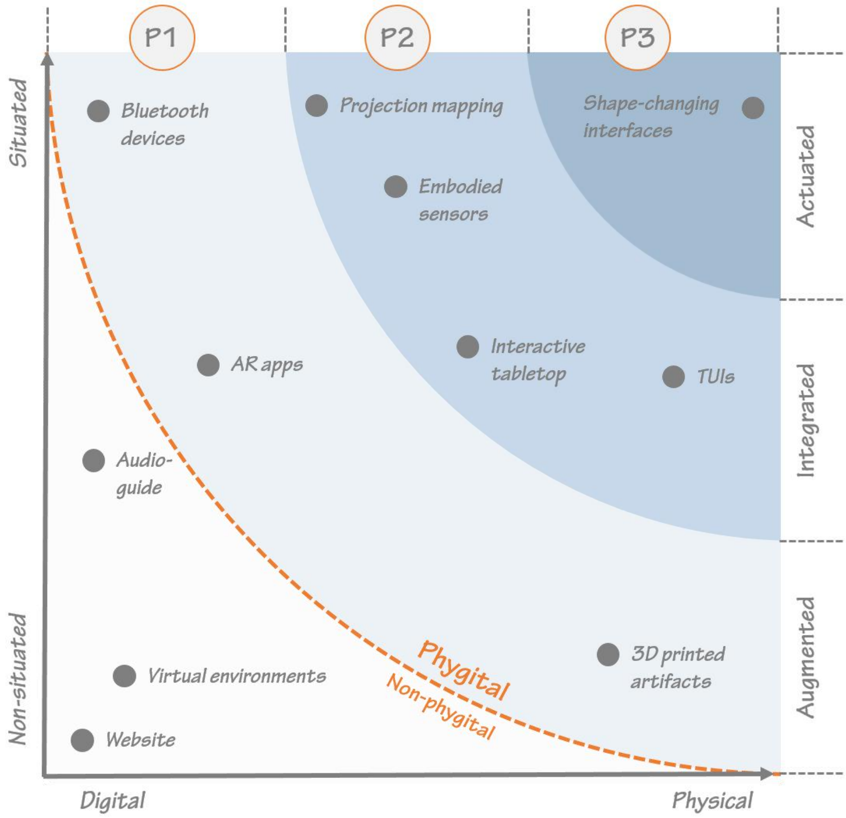


Figure 2-1: *Phygital heritage model, mapped along two characteristics: the physical affordance of information and the level of situatedness of how this information is communicated.*

An amended version of the model of *Phygital Heritage* is presented in (Chapter 7) based on the overall results of the different studies in the thesis.

- *Augmented (P1)* requires some form of continuous interaction between heritage objects or assets (physical) and electronic devices (digital). For instance, mobile augmented reality (AR) immerses visitors in a story by providing different information through texts, images and advanced 3D models via their portable devices [Marshall et al, 2016]. This category also includes the use of 'beacons' (small devices that transmit Bluetooth signal to visitors' smartphones), which allow for the mapping and recording of points of interest inside heritage buildings to provide contextual information [Mantova, 2016].
- *Integrated (P2)* requires users to interact with heritage objects via TUIs, which are capable of communicating information through the use of haptic rendering methods. TUIs provide users with more familiar physical objects and actions to explore, even to make sense of more abstract or less familiar digital representations. Most projection mappings also fall within this category, as its content communicates relevant contextual information, like the characteristics and cultural values of heritage (e.g. [Kim, 2015]).
- *Actuated (P3)* includes immersive and screen-less forms of interaction. Here, heritage artefacts become the output medium as the interface becomes embodied by the physical shape, behavior or materiality of the artefact itself. The emerging field of shape-changing technology forms a prime example [Rasmussen et al, 2016], capable to physically adapt the shape of objects based on users input, as users are actually able to interpret forms, and potentially the dynamic animations that cause these shape changes. Accordingly, material characteristics of heritage objects might convey meanings by appreciating physical manifestations of these objects.

2.3. Challenges of Phygital Heritage

Although the phygital approach promises various opportunities for heritage communication, phygital yet comes with several concerns and challenges. Blending the digital and the physical is technologically challenging, requiring advancements from computer science, electronics and physical design. The phygital requires that sensors and different types of actuators are embedded almost invisibly, such as projection and shape-changing interfaces, and that these combinations are meaningful, respectful and intuitive to be understood and used. Publicly accessible and touchable objects require solid and robust forms of technology, which cannot be simply taken away – or vice versa, should be cheap and sustainably replicable. As such, issues of cost and ease of replacement should be well considered [11]. Therefore, the phygital poses several questions in how such interfaces can be designed, implemented or evaluated. For instance, usually visitors are not allowed to touch heritage artefacts due to obvious preservation concerns. Although some museums utilize replicas to overcome this challenge, such replicas often lack ways of communicating tangible (e.g. texture, color, weight) and intangible (e.g. worth, value, stories) forms of information, which must then be presented separately.

On the other hand, TUIs can be perceived as being intuitive and playful, causing them to be used by children, hereby opening up new opportunities to facilitate learning through play. Nonetheless, museum visits should not only have an educational purpose, as museums are also a place for social interaction and participation with other visitors. For that, the concept of phygital heritage might provide new solutions in how technology can truly support multi-user and collaborative forms of interaction.

2.4. Conclusion

This paper argues how the field of cultural heritage forms an ideal application domain to exploit the seamless blending of both digital and physical qualities to communicate heritage information in more engaging, educational and meaningful ways. The paper introduced a concise model to denote the different categories of phygital heritage according to the level of physical affordance, such as how the features of an interface physically support or facilitate taking an action, and situatedness, which is about how the technology depends on the physical context to communicate information. The paper also recognized the most important challenges for future scientific studies related to phygital heritage. This model should therefore be considered as a first step towards supporting researchers to develop more integrated and contextualized interactive communication techniques of heritage information.

Chapter 3:
Saqqara Entrance Colonnade

This chapter has been previously published as:

Eslam Nofal et al. (2018.a). “The Role of Tangible Interaction to Communicate Tacit Knowledge of Built Heritage”, *Heritage* 2018, 1 (2), pp. 414-436, DOI: https://doi.org/10.3390/heritage1020028

Abstract

Meanings and values of built heritage vary from factual and explicit meanings which are relatively easy to present, to more tacit knowledge, which is typically more challenging to communicate due to its implicit and often abstract character. In this paper, we investigate how tangible interaction influences the communication of this tacit knowledge of built heritage, and how it affects the experience of visitors. Through a between-group comparative study in a real-world museum context, we examined how the tangible characteristics of an interactive prototype museum installation influence how visitors perceive a particular story containing tacit heritage knowledge. The communicated story relates a historical journey in ancient Egypt to the physical and architectural characteristics of the entrance colonnade at the Djoser Complex in Saqqara. Our experimental conditions consisted of an interactive navigation (input) and a passive representation (output) components, ranging from traditional digital displays to fully tangible means of interaction. We report on our findings, which showed various differences and commonalities between our three experimental conditions. We conclude with a number of discussion points and design recommendations: (a) to strive for balance between navigation and representation modalities in terms of affordance and the required cognitive effort; (b) to take advantage of physical representation and grasping, such as conveying particular physical details and characteristics; and (c) to consider design aspects of embodiment, physical abstraction and materiality for future research or potential further development of communicating the meanings and values of heritage.

3.1. Introduction

Our built heritage forms a unique asset, as it expresses the richness and diversity of our common past. Heritage sites and monuments should therefore not be interpreted just as physical constructions, but as tangible artefacts that represent meanings and values that might even change over time. We therefore consider how the built heritage can be interpreted as a communication process [Kepczynska-Walczak and Walczak, 2015], in which the different types of values and meanings can be perceived, understood and appreciated by a wide range of visitors. Typical values and meanings that originate from built heritage include factual and explicit meanings, such as shapes and forms, which are relatively easy to be graphically represented via text or images. Likewise, dimensions, which synthesize the proper understanding of the built heritage, are commonly communicated via drawings and sketches. Yet more intangible or tacit meanings and values, such as the skills, ideas and experiences that the heritage represents, are typically more challenging to communicate to visitors due to their implicit and often abstract character. Yet such tacit knowledge is particularly important to understand the complexity and richness of heritage as an experiential and communal concept that is not necessarily declarative or definitive. Tacit knowledge of built heritage includes, but is not limited to: (a) architectural qualities, such as how aspects of the work reinforce the oeuvre of a known or distinguished architect, the interrelationships of the different design styles within the artefact, the contributions to its environment, or particular structural or decorative aspects and their design process [D.A.H.G., 2011]; (b) cultural values, such as how the work has gained cultural significance with the passing of time, or how particular building characteristics illustrate specific societal developments; (c) aesthetic features, such as how the work corresponds to the sense of tradition and is manifested through an appreciation of cultural and historic characteristics [Milne, 2011]; or (d) symbolic significance, such as the symbolic aspects of what the work represents, or their embodied value in terms of their construction [Smith, 2010].

In particular, our research focuses on communicating tacit knowledge of built heritage. We are motivated by the emerging concept of heritage democratization [Rodéhn, 2015], which states how communication forms a crucial matter in heritage, as an exceptional vehicle for spreading knowledge and heritage values by collectively facilitating access and awareness for extended protection [Chiapparini, 2012]. By democratizing its communication beyond heritage professionals for conservation decisions [Fredheim and Khalaf, 2016], the significance of this tacit knowledge can be appreciated by a broader public such as to raise community awareness or to enable heritage visitors to appreciate heritage in more experiential ways.

During the past two decades, several emerging digital technologies already profoundly influenced the ways of disseminating and communicating cultural heritage [King et al, 2016]. These technologies vary in terms of their modality, immersion and integration into the physical manifestation of the heritage environment. For example, digital audio-guides in museums now offer immersive sound atmospheres that enrich the exploration of museum collections. Although these audio guides can be synchronized with individual trajectories [Bederson, 1995], their individual 'audio bubbles' [Petrelli et al, 2013] tend to isolate users insofar that they may hinder social or natural interactions between visitors themselves. Other technologies like digital displays focus on the communication of heritage values and meanings via the graphical user interface (GUI) such as via hand-held devices providing digital storytelling [Coenen et al, 2013; Ioannidis et al, 2013]; via large and sometimes interactive displays or multi-touch tabletops [Chu et al, 2015] that present textual or graphic heritage information, allowing multiple people to comprehend information and even enable the interaction of multiple people simultaneously, fostering different forms of socialization between them [Ardito et al, 2015]; or even more flexible active presentation modalities, such as projections [Marton et al, 2014] that are able to engage multiple museum visitors in more body-centric and thus physical ways.

Tangible interaction is an interdisciplinary field of research, spanning a variety of perspectives, including Human-Computer Interaction (HCI) and Interaction Design. Its research tends to investigate how computational and mechanical advancements can be combined to allow novel forms of natural manipulation and full-body interaction with data and information [Hornecker and Buur, 2006]. In comparison to GUIs, tangible user interfaces (TUIs) are believed to be relatively more intuitive, as TUIs tend to communicate meaning through their physical affordances [Macaranas et al, 2012], such as by mapping information into physical shapes and forms, or into its material attributes (e.g., size, shape, texture, color, weight). Because of these affordances, which reveal the implied interaction possibilities through the physical design features in apparently seamless and natural ways, TUIs tend to require little experience or skills to be operated, and can function as both input and output mediums [Shaer and Hornecker, 2010]. TUIs have also shown to possess significantly different qualities in comparison to commonly existing ways of heritage communication. For instance, TUIs tend to perform better in terms of recall because it requires multimodal ways of human perception to discover and decipher their meaning [Seo et al, 2015]. TUIs differ from touch surfaces in terms of their positive suitability in supporting collaborative and participative processes among users [Claes and Vande Moere, 2015], while their explicit touch and manipulation affordances have shown to attract more visitors towards more extensive forms of exploration during interactive exhibits [Ma et al, 2015]. The design of TUIs focuses on how tangibles represents digital information and how it empowers users to interact with this information [Wyeth, 2008]. This information is often represented by metaphoric [Fishkin, 2004] or symbolic [Ullmer and Ishii, 2000] forms via interaction modalities, which we call 'navigation' later in this paper. Because of these unique qualities, we believe tangible interaction forms a promising paradigm for communicating tacit knowledge of built heritage.

In fact, tangible interaction has already been scientifically investigated as a potential means to communicate different forms of heritage information. For instance, the European project meSch (mesch-project.eu) focuses on enabling forms of co-design between designers and heritage professionals by way of a do-it-yourself philosophy of making and experimenting. Recent outputs of this project include for instance, a book-like device that visitors carry with them during their visit in an outdoor heritage environment to support storytelling, as location-based auditory information is played when a magnetic bookmark is placed on a selected page of the book [Ciolfi et al, 2013]. In museums, 3D printed replicas of original artifacts are used to trigger digital narrative content projected on museum display cases [Marshall et al, 2016].

TUIs offer a spectrum of opportunities for museums with regard to the level of embodiment, focus of interaction, and targeting specific audiences to communicate the tangible and intangible values of heritage. First, applications of TUIs in museums vary in terms of how the museum artifact is embedded in the interface; from using the original artifact itself as an interaction device, such as triggering illuminations and auditory information by touching the artifacts [Rapetti, 2005], to a semi attached interaction, such as using a wooden magnifying lens with an integrated smartphone for allowing visitors to examine museum artifacts by pointing the lens close to them and then extra digital content (e.g., text, images or animations) is displayed on the smartphone [Van der Vaart and Damala, 2015], to more detached interaction when the original artifact and the interface are located in distant places in the museum for provoking visitors' curiosity to visit the artifact and to learn about it [Duranti, 2017]. Second, communicating information and values of cultural heritage through tangible interaction could be explicitly integrated into sensorized objects by focusing on their physicality [Capurro et al, 2015], or it could be implicitly integrated in a gesture or an action, focusing therefore on the act rather than the object itself [Duranti et al, 2016]. By performing specific actions, the visitor implicitly understands and experiences an intangible value related to a certain object. These actions could be performed to navigate 3D models, to compare several objects, or to experience the physical material properties of an object [Duranti, 2017]. Further, the tactile qualities of tangible interaction allow for interactive installations in museums that target specific audience [Duranti, 2017]. For instance, the mix of materialities encourages creativity for playful exploration and allows for educational opportunities in a children's exhibition [Taylor et al, 2015]. Moreover, the tactile exploration enables blind and visually impaired people to interact with heritage collections by touching specific hotspots on the artifact [Touch Graphics, 2015], or by navigating 3D surfaces via a smart ring in their fingers [D'Agnano et al, 2015] to trigger voice explanations.

However, little is known on whether and how tangible interaction is effective in communicating knowledge or meaning, let alone in the context of revealing tacit knowledge of built heritage in a museum context. In order to investigate this issue and to benchmark different tangible interaction and feedback modalities, we conducted a between-group comparative study in a real-world museum context. As tacit knowledge, we chose a particular story that relates the physical and architectural characteristics of the entrance colonnade at the Djoser Complex in Saqqara to the potential meaning of the historical journey along the Nile in ancient Egypt. We investigated how this symbolic significance and other architectural qualities were communicated to museum visitors based on their interaction with three different experimental conditions. We also examined their engagement during interaction and how it affects communicating tacit knowledge of built heritage. Each of the tested experimental conditions consisted of an interactive navigation (input) and a passive representation (output) components. As such, the three conditions differed from each other by one of the tangible modalities, ranging from a traditional digital display interface to fully tangible means of interaction.

3.2. Context

Most ancient Egyptian antiquities are characterized by tacit knowledge like historical values as well as distinctive architectural qualities, which all predominantly represent symbolic significance through association and context. We chose to communicate the tacit knowledge of the Djoser pyramid complex in Egypt specifically because: (a) the antiquity department at the Royal Museum of Art and History in Brussels already possessed significant historical and archeological expertise of this particular site; (b) we discovered that its architectural layout and features are comprised of a rich variety of distinctive architectural qualities that could potentially be represented via tangible interaction, such as its spatial proportions, number and style of columns, etc. which individually (c) symbolize a specific historical story that is sufficiently compelling and interesting to be communicated to a large, lay audience. As such, our study was deployed in close collaboration with the Antiquity Department of the Royal Museum of Art and History in Brussels. The museum possesses the largest collection of Egyptian antiquities in Belgium, including a monumental scale model of the Djoser pyramid complex in Saqqara that dates back to 1943. The fabrication of this scale model was managed by the Egyptologist Jean-Philippe Lauer, who considered Saqqara as a life-long commitment [Van Rinsveld, 1997]. Although the model was not publicly accessible at the time of our study, it might be featured in future exhibition designs, so that the empirical knowledge from our studies could form a foundation on which future tangible interaction approaches could be grounded.

The Djoser pyramid complex forms a mortuary precinct in Saqqara believed to be designed by Imhotep, one of the greatest known architects in ancient Egypt [Arnold, 2003]. It was built for pharaoh Djoser around the mid-27th century BCE, and is recognized as the world's oldest large-scale stone structure. Its entrance colonnade consists of a limestone ceiling, loaded by pairs of limestone fluted columns composed of drum shaped segments, all reaching a height of 6.6 m. The columns are not free-standing, but attached to their side wall by masonry projections, hereby composing 42 individual *niches*, which are the spaces created between adjacent columns (Figure 3-1, right). The combination of complex architectural features of this impressive entrance colonnade carries a peculiar cultural meaning, as its particular physical layout can possibly be associated to the historical journey the pharaoh undertook along the Nile to visit each of the 42 *nomes*, the administrative territorial divisions of ancient Egypt (Figure 3-1, left), and their local gods. Some Egyptologists propose that each *niche* in the entrance colonnade represented a shrine where the *nome* gods of ancient Egypt were accommodated during the *Heb-Sed*, a festival celebrating the continued rule of the king through rituals that symbolically rejuvenate him [Hermann, 1938], for opposing views see [Lauer, 1948]. This working hypothesis is believed to be plausible because the number of *niches* and *nomes* are equal (42). As such, the architect Imhotep may have designed the architectural layout of the colonnade to portray symbolically the Nile River, and consequently the end chamber would represent the Delta region.

In short, the historical hypothesis is that the processing of pharaoh Djoser along the corridor, passing by each *nome* shrine, represents and evokes a ritualized version of the pharaoh's journey along the Nile to visit each of the *nomes* and their local gods [Verner, 2001]. Our study hypothesis is that this tacit historical knowledge can be effectively communicated via tangible forms of interaction, which will lead to more collaborative forms of interaction and more profound recall of tacit heritage qualities by general museum visitors.

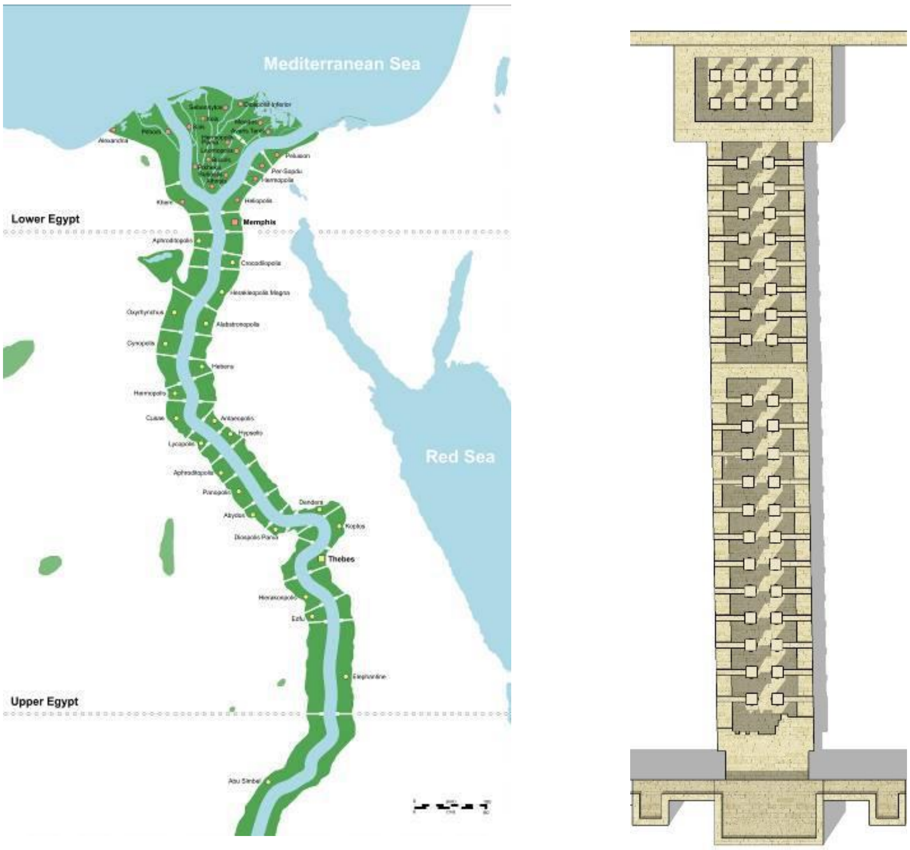


Figure 3-1: *The chosen tacit knowledge; the historical hypothesis that the 42 niches in the entrance colonnade (right) represent the 42 nomes of ancient Egypt along the Nile River (left); the end chamber would have represented the Delta; and that the processing of pharaoh Djoser along the corridor and passing by each nome shrine would have been a ritualized version of the pharaoh's journey along the Nile to visit each of the nomes and their local gods.*

3.3. Methodology

In order to recognize the causal influence of tangible interaction on the communication of tacit knowledge of built heritage, we based our experimental approach on a between-group comparative study design. This means that we compared the impact of different tangible interaction designs with each other, in a way that avoided participants to interact with more than one interaction approach so that no learning effects or other kinds of bias could occur.

3.3.1. Experimental Conditions

The evaluation study consisted of three different conditions. Each condition was comprised of a distinct interactive navigation (input) and a representation (output) component that differed in terms of modality as summarized in Table 3-1 and as illustrated in Figure 3-2.

Table 3-1: *Navigation and representation components of the three different conditions.*

	Touch-Dix	***Tang-Dix***	***Tang-Phys***
Navigation	touch screen	tangible installation	tangible installation
Representation	2.5D digital display	2.5D digital display	3D physical rendition

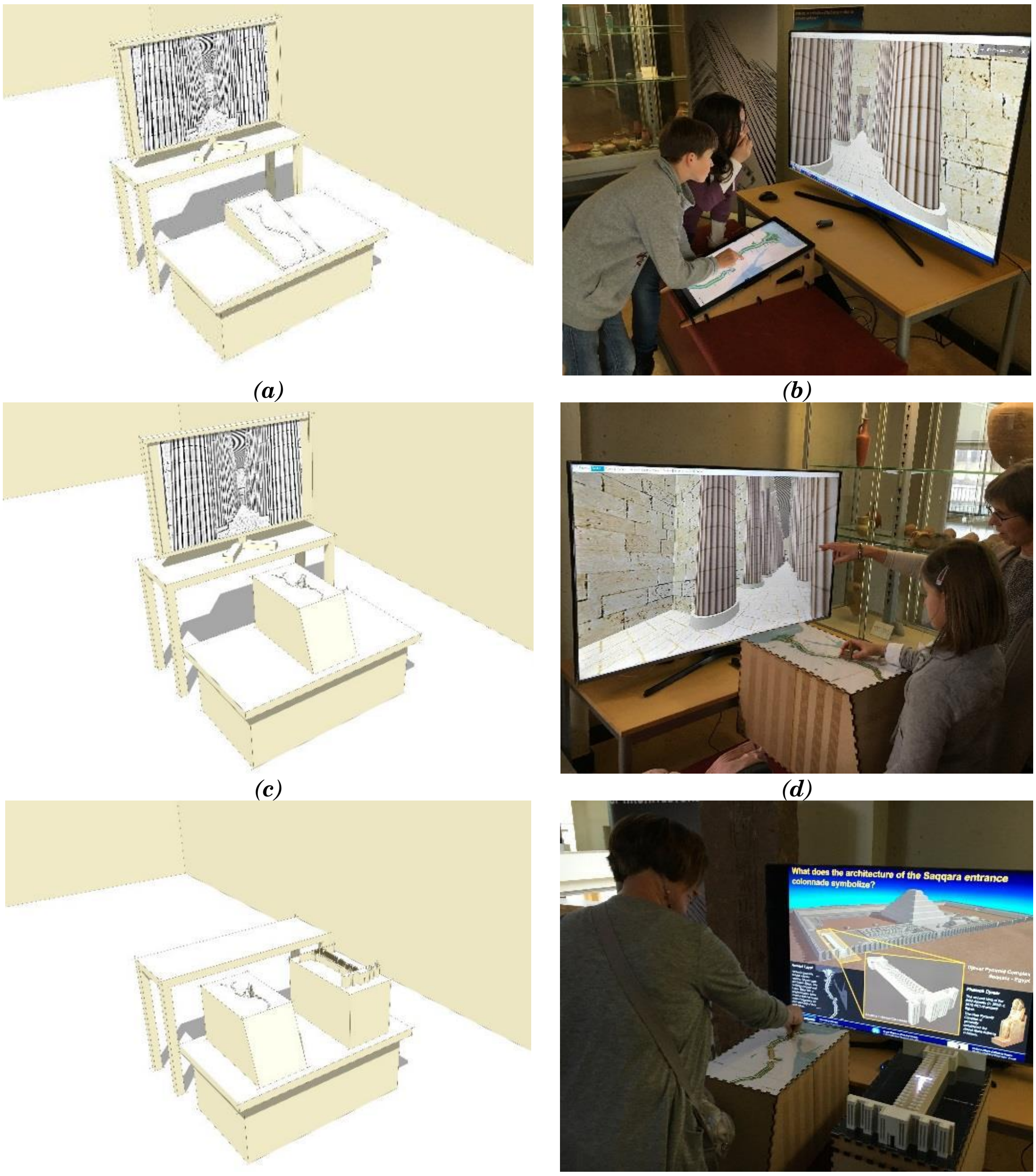


Figure 3-2*: Different conditions for communicating the architectural story of the entrance colonnade of Djoser Pyramid Complex: (a) and (b) touch navigation and digital representation; (c) and (d) tangible navigation and digital representation; and (e) and (f) tangible navigation and physical representation (in this condition, the informative poster was displayed on the larger LCD display behind the installation).*

In short, the *Touch-Dix* condition used a 'digital' modality in both navigation and representation components; the *Tang-Dix* condition used a 'tangible' modality for the navigation component; while the *Tang-Phys* condition included 'tangible' modalities for both components. The navigation component was based on interacting with a map of ancient Egypt that depicted the location of the territorial divisions of 42 *nomes*, as shown in Figure 3-1 (left). Participants were able to interact with the map either via moving around their finger on a common touch display (*Touch-Dix*) or via physically moving around a miniature 3D-printed statue of pharaoh Djoser on the map (*Tang-Dix* and *Tang-Phys*). In turn, the representation always consisted of a view of the entrance colonnade that dynamically changed according to the user input retrieved from the navigation component. The modality of this view either consisted of a 'digital' approach, i.e., a common LCD display depicting a 2.5D walk-through view of a rendered 3D model of the colonnade (*Touch-Dix* and *Tang-Dix*); or a 'tangible' approach, i.e., a physical scale model of the colonnade featuring a row of LED lights that lit up according to the navigation input, which users were able to pick up and touch (*Tang-Phys*).

3.3.1.1. Touch-Dix (Figure 3-2.a, and 3-2.b)[1]

The navigation modality in this condition occurred via a touch-enabled LCD display. Participants dragged a small 'you are here' icon along the Nile as depicted on a map of ancient Egypt. The position and rotation of this icon was directly translated to that of a camera viewpoint inside a virtual 3D model of the colonnade that was simultaneously displayed on a larger LCD screen in front of the smaller touch-enabled display. The real-time connection between the touch display and the 3D world was accomplished via the Edddison plugin (edddison.com) within the SketchUp application. A printed poster (A2 size) located next to this installation summarily explained the historical context, and included a close-up view of the entrance colonnade, a concise bio of pharaoh Djoser, a map showing the unification of ancient Egypt, and an evocative question to visitors "what does the architecture of Saqqara's entrance colonnade symbolize?".

3.3.1.2. Tang-Dix (Figure 3-2.c, and 3-2d)[2]

In the navigation modality of this condition, participants were invited to physically move a 3D-printed statue of pharaoh Djoser along a narrow slot representing the Nile River, which was equally shown on a map of ancient Egypt. Similarly to *Touch-Dix*, the relative position and rotation of the statue was directly linked to that of the camera viewpoint inside a virtual 3D model of the colonnade that was displayed on a large LCD screen. The relative location of the statue was tracked via a webcam underneath the map, which was then linked to the SketchUp model on the large LCD screen via a feature of the same Edddison plugin. Identically to *Touch-Dix*, participants were informed of the historical context via the printed poster.

3.3.1.3. Tang-Phys (Figure 3-2.e, and 3-2.f)[3]

The navigation modality was identical to *Tang-Dix*, yet moving the statue along the Nile River caused a sequential row of LED lights to illuminate (Figure 3-3.c) within a graspable and physical manifestation of the colonnade, to denote the position of the *nome* along the Nile with its corresponding *niche* (See the hypothesis in Figure 3-1). On a technical level, the distance of the physical statue was linked to a custom-developed electronic setup that controlled an Arduino LED strip that was integrated into the colonnade mock-up. During this condition, the informative poster was displayed on the larger LCD display behind the installation (Figure 3-2.f).

In order to better differentiate the aspects of immersion and interaction, the condition *Tang-Phys* was divided in two different sub-conditions. In the *fixed* sub-

[1] A video illustration of *Touch-Dix* condition is available on: https://vimeo.com/337470310

[2] A video illustration of *Tang-Dix* condition is available on: https://vimeo.com/336834958

[3] A video illustration of *Tang-Phys* condition is available on: https://vimeo.com/337470276

condition, the colonnade scale model was fixed unto the installation, meaning that participants were only able to look and touch the physical model from above (Figure 3-3.a). In the *graspable* sub-condition, participants were allowed to pick up the model to look through it, potentially increasing the comprehension of spatial aspects [Voigt and Martens, 2006] such as scale and proportionality (Figure 3-3.b).

(a) ***(b)*** ***(c)***

Figure 3-3: *Illustration of the different sub-conditions of Tang-Phys: (a) Fixed: the colonnade scale model is fixed unto the installation; (b) Graspable: visitors are allowed to pick the model up; and (c) close-up view of the colonnade model from inside, showing the 3D printed fluted columns and the LED lights in each niche.*

3.3.2. Evaluation Methods

The evaluation study deployed a mixed-method methodology, consisting of in-situ observations, semi-structured interviews, and a standardized user experience questionnaire.

3.3.2.1. Observation

During the experimental part of the study, all participants' interactions were video-recorded and observed, and then manually listed and analyzed in an Excel spreadsheet. The level of user engagement was derived by the duration of interaction, the apparent focus of attention while interacting and any form of social interaction with other person(s) nearby. The resulting observation data was chronologically mapped and then labelled in terms of user behavior, such as whether a participant focused on the navigation or the representation component, or both simultaneously; or whether they started discussing with each other; and whether these social interactions targeted the purpose of the installation or the sharing of their preliminary comprehension of it. We also logged any discussion with the interviewer, and whether and for how long they looked at the informative poster.

3.3.2.2. Semi-Structures Interview

After the experimental phase of the study, participants were invited to partake in a semi-structured interview that was audio-recorded. The questions focused on whether and how the participant comprehended the tacit knowledge of the colonnade, such as the symbolic relationships between the map of Egypt and the architectural colonnade layout. The interview also captured the participant's spatial comprehension of the colonnade layout, in order to benchmark how the architectural qualities of the space (e.g., dimensions and proportions, shape and flutedness of the columns) were perceived and internalized. For instance, participants were requested to describe the physical appearance (e.g., shape, number, color, material, etc.) of the columns when they voluntarily mentioned them during the interview. All participants were invited to estimate and report on the dimensions of the colonnade's width and height by sketching a cross-section of the colonnade on a grid paper that featured a human figure to illustrate the relative scale. In the case of a collaborative or group participation, each individual participant was asked to add his/her estimation on the same grid paper by a different color. Participants were also asked about their level of appreciation for these kind of installations, in an attempt to open up the interview towards more subjective answers that could explain the more quantitative responses before. All answers from the interviews were then manually analyzed using an Excel spreadsheet, where we collected the understanding of the symbolic significance, and calculated the averages and median values for each condition, as summarized in Table 3-2.

3.3.2.3. User Experience Questionnaire (UEQ)

Subsequently to the interview phase, participants were asked to fill in a standardized user experience questionnaire (ueq-online.org). The UEQ has proven to be an efficient assessment of the user experience of an interaction design [Laugwitz et al, 2008] and allowed participants to express their subjective feelings, impressions or attitudes in a statistically valid manner. The questionnaire consisted of six different scales with 26 items in total, covering a relatively comprehensive impression of user experience, including: (1) *attractiveness*, or the general impression of users, such as whether users liked or disliked it; (2) *efficiency*, such as whether users were able to use the installation efficiently, and whether its user interface looked organized; (3) *perspicuity*, or whether the installation was easy to understand in how it can be used; (4) *dependability*, or whether the user felt in control of the interaction in terms of security and predictability; (5) *stimulation*: whether they found it interesting and exciting to use; and finally, (6) *novelty*, in that the installation was considered to be innovative and creative.

3.3.3. Study Setup

The evaluation phase of this study commenced with a low-fidelity test session at our research lab with only a few participants. This test was followed by a two-day pilot study in the real museum environment, before we carried out the large-scale study during approximately two weeks. All participants first signed an informed consent form to confirm that they voluntarily participated and that the results of this research can be used only for scientific purposes.

3.3.3.1. Lab Study

Six volunteers (i.e., research associates not directly associated with this research) interacted with the three different installations in differing orders for around 10 min. Open interviews gauged whether they were able to intuitively use the installations, understood the symbolic link between the colonnade and the map, and remembered some of the architectural qualities. The subsequent analysis of their feedback led to several technical (e.g., the way the LED lights lit up), methodical (e.g., the phrasing of questions) and ergonomic (e.g., the table height of the installation, the graphical and textual readability of the map) alterations.

3.3.3.2. Pilot Study

The two-day pilot study occurred in the main showroom of the Egyptian collections at the Royal Museums of Art and History (Figure 3-4). It aimed to reveal any obvious usability or other user experiential issues within an ecologically valid context, such as whether lay museum visitors could intuitively understand how to interact with each installation. Each condition was introduced by a brief explanation about the general context of the colonnade (i.e., location and historical period) and the purpose of interacting with the installation (i.e., to explore the architectural symbolism of the entrance colonnade). The pilot-study consisted of 13 participants, participating individually or in group, including couples and groups of children on a museum school trip. The results and implications of this pilot study were briefly reported in [Nofal et al, 2016].

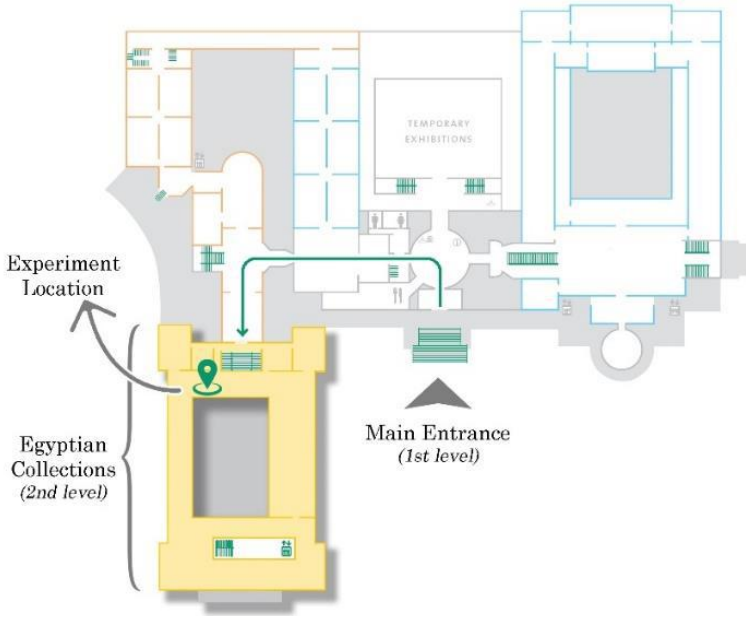


Figure 3-4: *Floor plan of the Royal Museums of Art and History in Brussels, indicating the location of the experiment in the main showroom of the Egyptian collections at the Antiquity Department.*

3.3.3.3. Final Study

Based on the results of the pilot study, several more modifications were implemented, such as: (1) the informative poster was printed in a larger size (A2 instead of A3) to be more prominently visible; (2) the 7″ tablet computer was replaced by a larger 21″ touch screen to increase the usability and accessibility of the navigation input; (3) the 21″ output display was replaced by a 52″ version to increase its prominence and general legibility; and (4) the evocative question was changed to be clearer about the symbolic significance of the entrance colonnade. The final study was conducted during five days at different times of day (mornings and afternoons during weekdays and weekends) over a total period of two weeks in order to reach varying types of museum visitors. Naturally, the three conditions were equally distributed over time in a random order to avoid that specific conditions were only tested by specific types of visitors (e.g., young pupils) or that learning effects occurred between museum visitors.

3.4. Results

The final comparative study involved a total of 42 participants, almost evenly distributed over the three different conditions (13 *Touch-Dix*, 14 *Tang-Dix*, and 15 *Tang-Phys*), who participated individually (10) or in groups (32), including couples, friends, or parents with children on a family museum visit. Only one group composed of two visitors do not know each other who socially engaged only in the sake of participating in the experiment. Participants varied in terms of gender (i.e., 4 males, 14 females, and 24 mixed groups of males and females), age range (i.e., children, teenagers, adults, and elderly), and the purpose of their museum visit (i.e., 2 school or university visits, 13 family visits, 13 local tourists, 13 international tourists, and 1 museum staff member). Based on the observations, interviews, and the user experience questionnaire, our findings are categorized into aspects relating to the communication of tacit knowledge and the user engagement.

3.4.1. Communication of Tacit Knowledge

This section describes how differences in the navigation and representation features of TUIs impact its ability to communicate tacit heritage knowledge in a museum context, including its symbolic significance and architectural qualities.

3.4.1.1. Comprehension of the Symbolic Significance

Our results indicate that the level of understanding of the symbolic relationship differs between the three conditions. In *Touch-Dix*, 39% of the participants (5, N = 13) immediately mentioned the link when they were asked about what did they learn from interacting with the installation, e.g., *"I think I was quite fast in understanding that link … for me, it was quite clear"* (participant 18). Another 39% of the participants (5, N = 13) described the link when they were asked more specifically during the interview about the corridor's symbolic representation. The remaining participants (3, N = 15) considered it difficult and commented on its complexity after it was explained to them *"you see a corridor and a lot of pillars, but to link it to the Nile is too far"* (participant 21).

Condition *Tang-Dix* proved more challenging, as there were only 3 participants (N = 14) who mentioned the symbolism immediately when they were asked what they learned from their interaction. However, participants found this insight not easy: *"I was moving this control (statue) through the river, and at the same time I was thinking why I am moving on the river, it was not related to the display … I think it is not easy to make a connection"* (participant 6), whereas 5 participants (N = 14) in the *Tang-Dix* condition only described the meaning during the interview when they were asked more specifically about the corridor's symbolic representation. For instance, *"if you only put this in front of visitors, nobody will get it"* (participant 11).

In contrast, condition *Tang-Phys* succeeded better in conveying the symbolic significance as 14 participants (N = 15), of which 10 in *graspable* sub-condition (N = 10) and 4 in *fixed* sub-condition (N = 5), mentioned the symbolic meaning when they were asked about what they learned from their interaction: *"it was evident when we are moving, the light is moving, so it was the Nile. As the Nile is the spine of Egypt, then it is Egypt"* (participant 27). Participants noted that they gained this knowledge only by interacting with this condition, as *"I did not know it was represented by the building. Now, because I saw the lights, I understand why the building was built"* (participant 30). Some participants reflected even upon the larger context of this insight. For instance, in *Tang-Phys* condition a participant mentioned that *"it was clear that this building was [built] at a unification period"* (participant 27), as he linked the story to the ancient Egyptian history when Egypt was divided into two regions, a historical fact that was also illustrated in the informative poster.

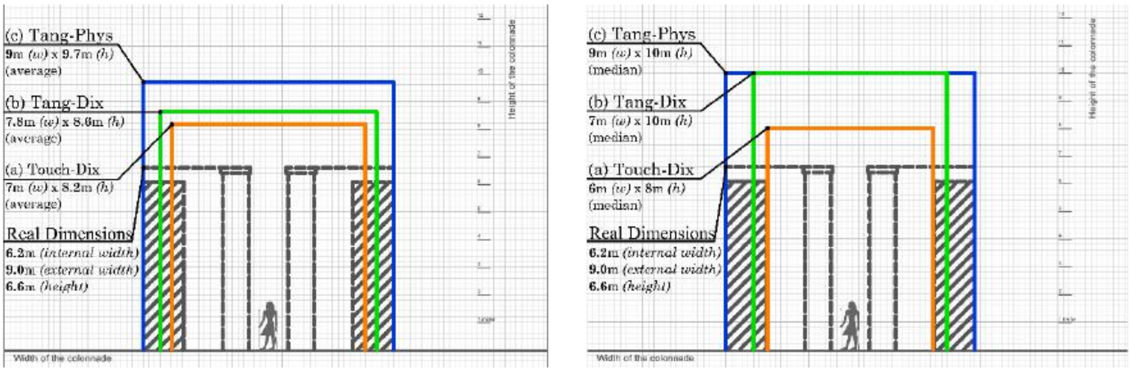
With regard to prior experience, we had 10 participants who previously visited the Saqqara site, as indicated in Table 3-2. Our results show no direct effect on the intuitive understanding of the symbolic meaning of the story (i.e., none of them from *Touch-Dix* (N = 3), only one from *Tang-Dix* (N = 4), and 2 from *Tang-Phys* (N = 3)). Further, it was challenging to extract the age-related differences regarding the understanding of the symbolic significance, as for instance all children visitors participated in groups with adults or elderly. Among groups with children, 3 groups intuitively understood the meaning from *Touch-Dix* (N = 4), 1 from *Tang-Dix* (N = 2), and 3 from *Tang-Phys* (N = 3). We noticed that the role of interacting with devices was dedicated mostly to children, while parents were focusing more on the poster and the map to understand the meaningful relationship; e.g., a parent from *Touch-Dix* condition: *"I was looking at the image (poster) and the map, not at the 3D model"* (participant 42).

3.4.1.2. Communication of Architectural Qualities

Participants described the colonnade as a linear space with a large number of columns and unclosed chambers between them (*niches*). When they were asked to estimate the number of the columns in the corridor (44), their answers in digital display conditions (*Touch-Dix* and *Tang-Dix*) were relatively correct, estimating their number as (53, avg.; 45, median) in *Touch-Dix* condition, and (51, avg.; 50, median) in *Tang-Dix* condition. However, in condition *Tang-Phys*, they tended to overestimate the number of columns (69, avg.; 49, median).

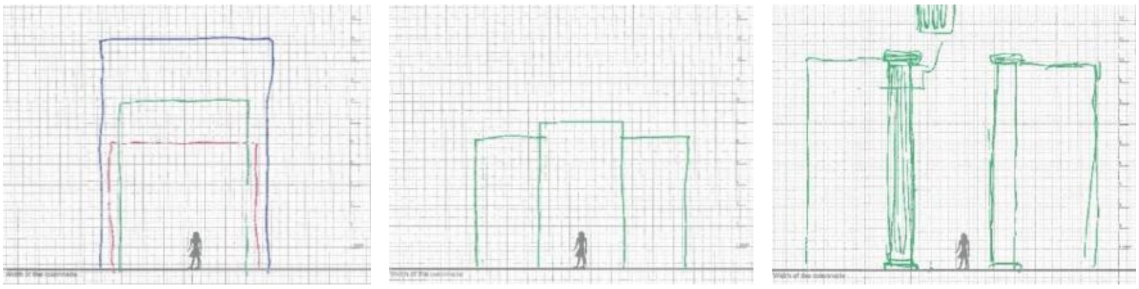
- *Spatial dimensions and proportions*

The participants' perception of the length of the colonnade varied from the actual length (56 m) to relatively large overestimations towards hundreds of meters. The average and median of their estimations per each condition were calculated and listed in Table 3-2. The average in the conditions of digital representation was quite convergent; 187 m in *Touch-Dix* and 162 m in *Tang-Dix* (medians are 150 m, and 75 m respectively). In *Tang-Phys* condition, the average of their estimations was 308 m because of a few outliers (median is 100 m). Although most participants initially hesitated to sketch the colonnade's dimensions on the grid paper due to a sense of social embarrassment or self-perceived poor drawing skills, all participants eventually sketched the requested section of the colonnade (Figure 3-5). Some of them even voluntarily used this opportunity to depict specific details, such as the ceiling's levels (Figure 3-6.b) and the fluted columns (Figure 3-6.c). Participants varied in estimating the height from approximately double the standard floor height, which is relatively correct (6.60 m), to somehow overestimations till 12 m in all conditions. However, their perception of the width varied between the digital representations conditions to the tangible scale model, as indicated in Figure 3-5 and Table 3-2. The estimated width in *Touch-Dix* and *Tang-Dix* conditions corresponded well with the actual internal width (i.e., inside) of the colonnade, whereas in the *Tang-Phys* condition, the external width (i.e., including the width of the outer walls) was perceived instead, as illustrated in Figure 3-5. Moreover, we calculated the width-to-height ratio in order to evaluate participants' perception of the proportional relationships of the space instead of absolute values of dimensions, as people tend to perceive spatial dimensions improperly through digital displays because of the limited field of view [Henry and Furness, 1993]. As such, we discovered that the ratio estimations conformed to the previous results, as illustrated in both Table 3-2 and in Figure 3-5.



(a) ***(b)***

Figure 3-5: *Calculated average (a) and median 'middle value' (b) of the estimated dimensions for the three conditions compared to the real dimensions; Tang-Phys (in blue), Tang-Dix (in green), Touch-Dix (in orange), and the actual dimensions (in black).*



(a) ***(b)*** ***(c)***

Figure 3-6: *Samples of participants' estimation of the colonnade dimensions; (a) sample from Touch-Dix; estimating the dimensions in different colors of a group participation; (b) sample from Tang-Dix; perceiving the ceiling's levels in both main corridor and side niches; and (c) sample from Tang-Phys; perceiving the fluted columns and sketching their details.*

Since spatial estimations seem to vary significantly between participants, making potential generalizations from these results is complex. Even in a group of multiple participants there existed different estimations of the spatial dimensions (e.g., Figure 3-6.a). For the more traditional digital representations, some participants perceived the steps of the ceiling (e.g., Figure 3-6.b), an observation that did not occur in *Tang-Phys* as the physical model was fabricated as a cross-section of the building, having no ceiling.

- *Shape, color and materiality of columns*

In the digital representation conditions (i.e., *Touch-Dix* and *Tang-Dix*), most participants (22, N = 27) correctly described the columns as having a rounded shape. Moreover, 10 participants (N = 13) in *Touch-Dix* condition and 8 participants (N = 14) in *Tang-Dix* condition mentioned that the columns were not smooth, but were fluted with vertical grooves. In condition *Tang-Phys*, some participants (5, N = 15) thought that the columns had a square or a rectangular shape, a perception that might well be the result of the top view that highlighted the square caps rather than section of the columns. *"Normally, columns in ancient Egypt are cylinders, but these are not. They were made of lines and angles. I even have the impression that they are not circular. But now thinking logically, I haven't seen any rectangular columns, they are always kind of circular, although the upper part (cap) could have been rectangle or square"* (participant 27). However, 9 participants in *Tang-Phys* condition (N = 15) mentioned that the columns were rounded and fluted, with one participant even drawing a detailed view of this flutedness as shown in Figure 3-6.c. It is worth mentioning that within the *graspable* sub-condition of *Tang-Phys*, 7 participants (N = 10) perceived the flutedness of columns, while only 2 participants (N = 5) perceived it in the *fixed* sub-condition.

Participants also perceived other architectural qualities, such as the color (i.e., beige) and the materials (i.e., sand stone) in the digital representation conditions. However, as those qualities were not readily visible in condition *Tang-Phys* as the scale model was fabricated as a white, monotonous sculpture, we do not consider these for further analysis.

Table 3-2: *Quantitative results of the final study in terms of user profiles, communication of tacit knowledge (symbolic significance and architectural qualities), and user engagement.*

		Touch-Dix		***Tang-Dix***		***Tang-Phys***	
User Profile	Participants (n).	13		14		15	
	Participation type (individual, group).	1	12	4	10	5	10
	Regularly visiting museums (n, %).	12	92.3%	14	100.0%	12	80%
	Familiar with interactive designs (n, %).	5	38.5%	8	57.1%	7	47%
	Previously visited Saqqara (n, %).	3	23.1%	4	28.6%	3	20%
Symbolic Significance	Participants who intuitively understood the symbolic meaning of the story (n, %).	5	38.5%	3	21.4%	14	93.3%
	Participants who understood the meaning only after asking questions about the representation (n, %).	5	38.5%	5	35.7%	1	6.6%
	Total participants who understood the meaning (the link between the map and the building).	10	76.9%	8	57.1%	15	100%

Architectural Qualities	Estimated number of columns (avg., median); original number is 42.	53	45	51	50	69	49
	Estimated length of the corridor (avg., median); original length is 56 m.	187 m	150 m	162 m	75 m	308 m	100 m
	Estimated height of the corridor (avg., median); original height is 6.6 m.	8.17 m	8 m	8.62 m	10 m	9.71 m	10 m
	Estimated width of the corridor (avg., median); original width is 9 m (external) and 6.2 m (internal).	6.95 m	6 m	7.79 m	7 m	9 m	9 m
	Calculated ratio width to height (avg., median); ratio is 1.36 (external width) and 0.92 (internal width).	0.890	0.75	0.954	1.0	0.965	0.9
	Participants who perceived the fluted columns (n, %)	10	76.9%	8	57.1%	9	60%
User Engagement	Time of interaction (avg., median).	179 s	130 s	182 s	165 s	180 s	160 s
	Level of appreciation: Don't like (n, %).	2	15.4%	0	0%	0	0%
	Neutral (n, %).	2	15.4%	5	35.7%	0	0%
	Like it (n, %).	5	38.5%	7	50%	9	60%
	Like it very much (n, %).	4	30.7%	2	14.3%	6	40%

3.4.2. User Engagement

This section describes the engagement of users in terms of their apparent focus of attention during interaction, their replies on the user experience questionnaire, and their forms of engagement and appreciation.

3.4.2.1. Chronological Analysis

Participants focused their attention on varying aspects during the interactive exploration process of each condition. Figure 3-7 demonstrates the chronological analysis of the three conditions, each row in the figure maps the interactions of a single participant along a horizontal timeline. Consequently, more yellow (i.e., focus on representation) can be noticed in condition *Tang-Dix*, while the green color (i.e., focus on navigation) can be noticed more during the interactions with conditions *Touch-Dix* and *Tang-Phys*. These patterns denote that condition *Tang-Dix* encouraged participants to focus more on the representation element (digital display), while the other two conditions (*Touch-Dix* and *Tang-Phys*) allowed participants to distribute their attention on both the representation (i.e., the digital display and 3D physical rendition) and the navigation (touch screen and tangible installation) elements. Moreover, we found a correlation between the visual attention of participants and their understanding of the cultural knowledge. As participants' focus of attention in *Tang-Dix* was less on navigation, and more on the digital representation on the screen (Figure 3-7); *Tang-Dix* condition attained the lowest percentage of understanding the story as indicated in Table 3-2. In contrast, the simultaneous focus of attention between navigation and representation in *Tang-Phys* resulted in better understanding of the symbolic significance of the colonnade.

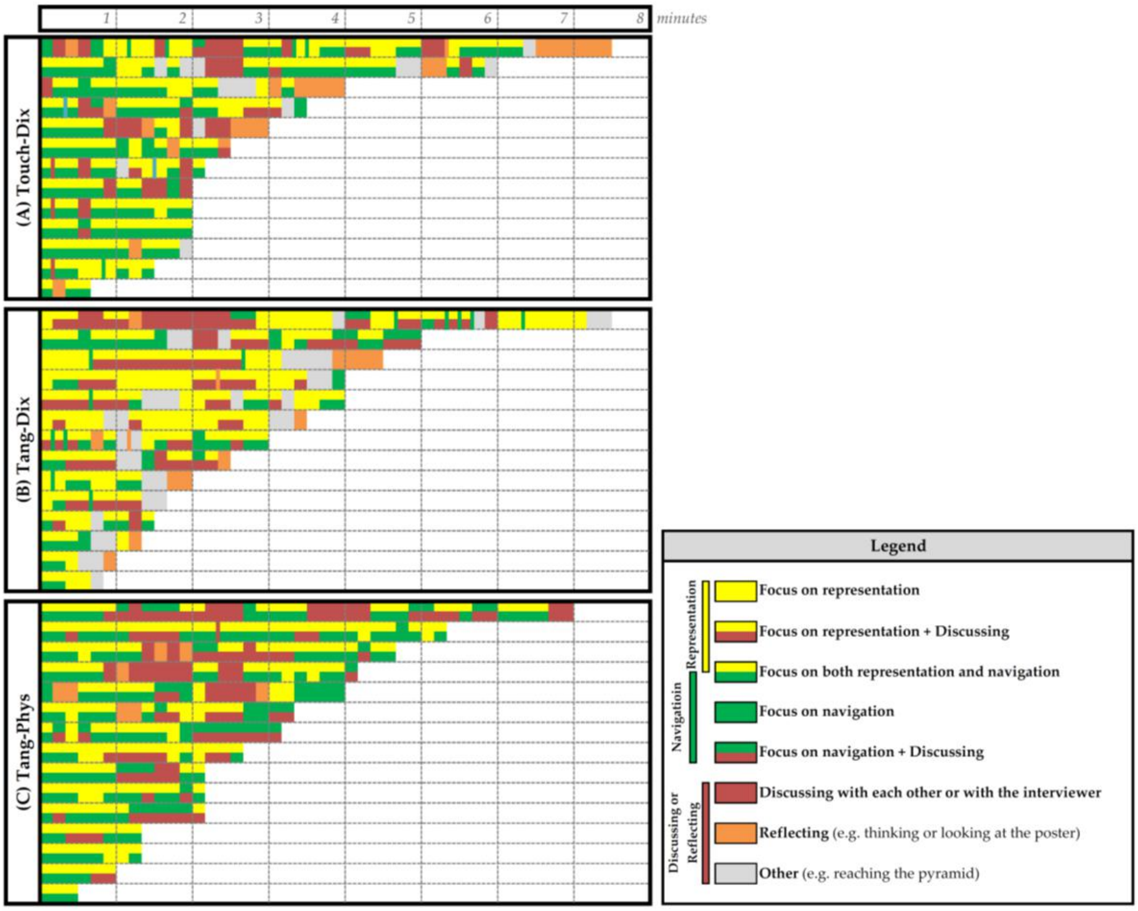


Figure 3-7: Chronological analysis of the participants' focus of attention while interacting with the three conditions.

Although all three conditions had the attention of a relatively similar number of participant groups (i.e., 12 in *Touch-Dix* (N = 13), 10 in *Tang-Dix* (N = 14), and 10 in *Tang-Phys* (N = 15)), the social interaction between the participants themselves was more noticeable during condition *Tang-Dix*. In contrast, there was somewhat less interaction in condition *Tang-Phys*, while in condition *Touch-Dix* the social interaction between the participants was much less than with the other two conditions.

3.4.2.2. User Experience Questionnaire (UEQ)

All UEQ items are scaled from −3 (representing the most negative answer) to +3 (representing the most positive answer, when 0 is a neutral answer). The Alpha-Coefficient value showed a high consistency for the items of attractiveness, stimulation, and novelty scales in all conditions. In contrast, the value was lower than 0.7 for the perspicuity scale in *Touch-Dix*, in efficiency scale in *Tang-Dix*, and in dependability scale for all conditions, meaning that these questions were probably misinterpreted or interpreted in a direction that does not reflect the intention of the participants within the context of UEQ [Rauschenberger et al, 2013].

As shown in Figure 3-8, the three conditions were statistically compared on the basis of the means for each UEQ scale. As the differences between the conditions are not significant for each of the scales (p-value is >0.05 in t-test), statistically valid generalizations are impossible. However, the results might still demonstrate some tendencies and trends in how each condition performed. For instance, *Tang-Phys* is more positive in attractiveness, perspicuity, efficiency and dependability scales, while *Tang-Dix* shows a positive performance in stimulation scale, and *Touch-Dix* in novelty scale.

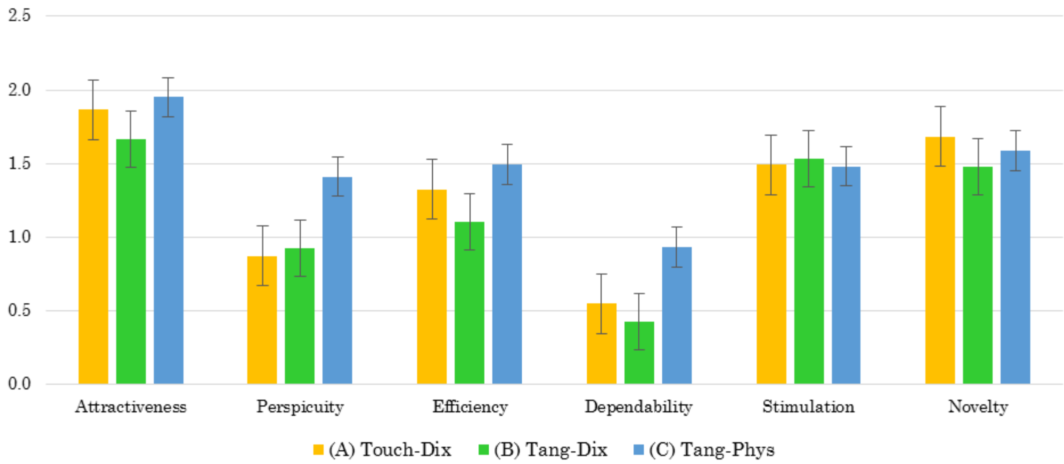


Figure 3-8: *Comparison among the three experimental conditions concerning the scales of the UEQ (the error bars represent the 95% confidence intervals of the scale mean).*

3.4.2.3. Engagement and Appreciation

In general, individual participants spent less time interacting (133 s, avg.; 85 s, median) in comparison to groups of participants (195 s, avg.; 180 s, median), as the discussion between group members encouraged them to explore the installation more. When comparing the different conditions, participants spent more time in case of tangible navigation; i.e., *Tang-Dix* (182 s, avg.; 165 s, median) and *Tang-Phys* (180 s, avg.; 160 s, median), compared to *Touch-Dix* (179 s, avg.; 130 s, median).

While the UEQ results demonstrate no significant differences between the conditions for all of the UEQ scales, participants seemed to have interpreted and appreciated the conditions differently. For instance, the concept of gaining new knowledge was mentioned 7 times in the context of *Tang-Phys* condition (N = 15) *"I like it because I learned something new"* (participant 38), and the concept of interactive experience in museums was mentioned 4 times in the same condition *"actually I like this installation very much because it is smartly done*" (participant 33). The condition *Tang-Dix* seemed less appreciated by participants (Figure 3-9), as 7 participants (N = 14) thought it required more explanation to be more appreciated, *"if you have explanation on the side, it may be clear"* (participant 12) and *"I like it now when you tell me the story, but before … not"* (participant 7). We have the impression that participants seemed to even less appreciate the *Touch-Dix* condition (Figure 3-9), mainly because of the lack of immersion when looking at the 2.5D representation of the colonnade *"it was too simple to grab my attention, and I was not immersed in it"* (participant 42), and possibly because they felt a bit frustrated *"oh, we tried every direction, and we see only columns"* (participant 21).

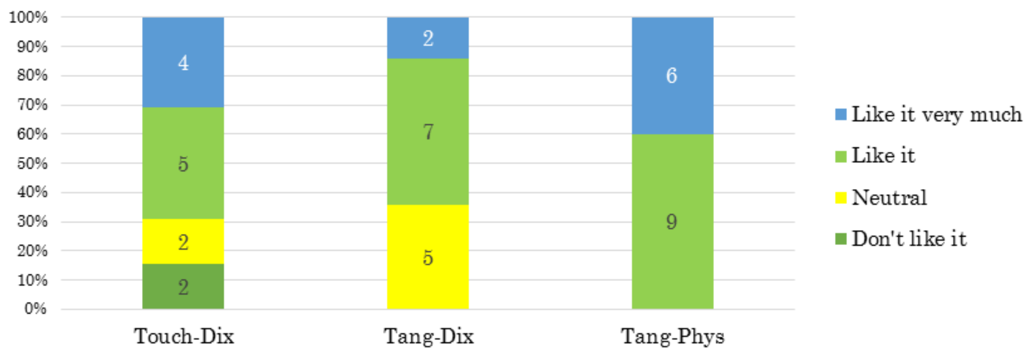


Figure 3-9: *The percentage and number of participants with each level of appreciation for the three conditions.*

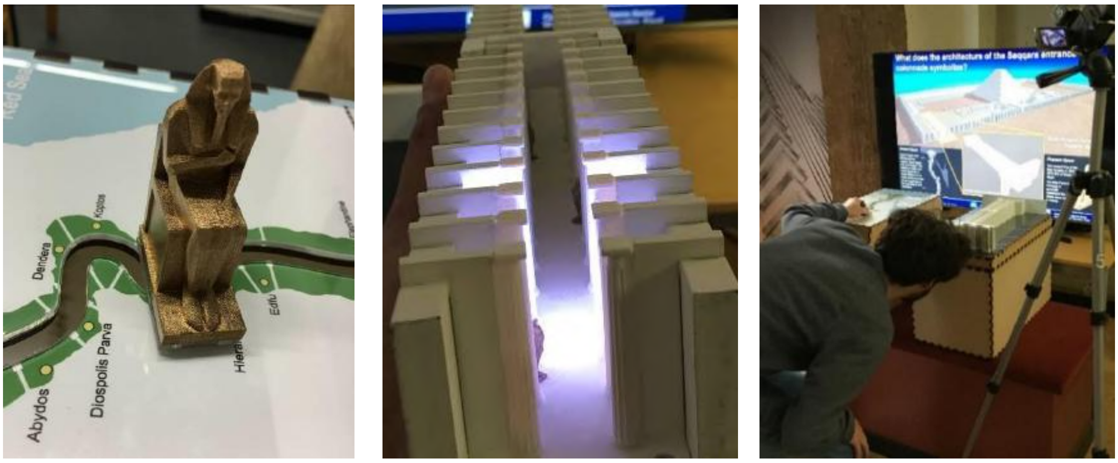
3.5. Discussion

In this section, we discuss the implications of our findings from this study with relevance to future research or potential further development of communicating heritage via tangible interaction. On the whole, one could note that *Touch-Dix* participants estimated the spatial features like dimensions (i.e., internal width) and quantity of major architectural elements relatively well. The condition *Tang-Dix* was better in stimulating social interactions among participants, who focused more on the output medium. Finally, the results of *Tang-Phys* show that it was better in conveying the symbolic significance of the colonnade, and it was more positively judged in the UEQ. Participants in that condition were more accurate in estimating the external width of the colonnade. In the *graspable* sub-condition, many perceived particular physical characteristics, i.e., the flutedness of the columns.

3.5.1. Role of Navigation

The design of our installations defined a new vocabulary of actions (e.g., similar to [Marshall et al, 2016; Duranti, 2017; Capurro et al, 2015; Taylor et al, 2015]), and the visitors were required to perform these actions in order to achieve certain goals (i.e., capturing the cultural knowledge). All three conditions were specifically designed to communicate the same tacit heritage knowledge by allowing participants to construct a meaningful link between an interactive navigation and the dynamic representation. Yet we observed that the actual effectiveness of linking and sense-making depended on the cognitive effort required to operate the tangible interaction interface, which consisted of the simultaneous use of an input (navigation) and output modality (representation). More specifically, the touch display in condition *Touch-Dix* proved harder to discover and then to operate, particularly when combined with a visual-centered output modality. We observed that the touch display affordance was mainly provided via the navigation component, while the visual attention of participants was constantly required in order to observe the relative position of their finger on the map, displayed on the screen (i.e., flat glass surface). In contrast, moving a physical object (i.e., the 3D printed statue of the pharaoh) along a groove possessed sufficient intuitive affordances and tangible guidance so that most visual attention could be dedicated to the output modality (representation) in *Tang-Dix* condition.

Accordingly, we believe that an equilibrium needs to be sought between the affordances and cognitive effort required when combining tangible interaction navigation and representation modalities. As participants' focus of attention in *Tang-Dix* was less on navigation, and more on the digital representation on the screen (Figure 3-7); *Tang-Dix* condition attained the lowest percentage of understanding the story as indicated in Table 3-2. In contrast, the seamless integration of navigation and representation in *Tang-Phys* resulted in better understanding of the symbolic significance of the colonnade. For instance, participants were able to do two simultaneous actions; tactile navigation and bringing their eyes to eye-level in the scale model (Figure 3-10.c). This was possible because the two actions are relatively usable and not requiring visual focus. The link between navigation and representation could cause a sort of distraction if it is not well considered in design [Duranti, 2017]. More specifically, only a single modality should require the conscious discovery of new affordances from the user, or require much and continuous cognitive effort to be operated. Yet the choice of these modalities might well depend on the specific focus or narrative of the intended communication. For instance, when intending that museum visitors should focus on the Nile, a touch display might be more suited.



(a) (b) (c)

Figure 3-10: *The different embodied metaphors of Tang-Phys condition; (a) the 3D printed statue of the pharaoh moving along the Nile River, (b) the fluted columns are physically printed in the 3D model, and (c) people feel 'inside the space' by looking through it.*

3.5.2. Role of Physical Representation

The level of realism, the physical construction and the manipulation features of a 3D scale model influences how people observe and remember architectural qualities, particularly when compared to a 2.5D interactive walk-through rendering. In the condition of physical representation (i.e., *Tang-Phys*), most participants understood intuitively the symbolic significance between the colonnade and the map. We believe that *Tang-Phys* enabled the communication of the symbolic significance because of the direct link between the movement of the statue along the Nile and the corresponding lights in the physical colonnade, that was easy to perceive as *"the parallelism of the colonnade and the map was too easy … with lights, it is evident"* (participant 38). As the digital representation conditions (*Touch-Dix* and *Tang-Dix*) reached a relatively lower percentage of participants who readily understood this symbolic significance (as shown in Table 3-2), understanding the link between the navigation and representation was more ambiguous and more challenging, probably because *"it was contradictory to move the control (statue) through the river, and at the same time to see the building"* (participant 6) from *Tang-Dix* condition. On the other hand, we observed several unexpected results in *Tang-Phys* condition, particularly regarding how participants perceived or remembered certain architectural qualities. For instance, participants perceived the spatial proportions differently. The average estimated width of the colonnade in *Tang-Phys* condition was more or less the correct external width including the width of the outer walls, whereas the length was somehow overestimated. The shape of the columns were perceived by 6 participants (N = 15) as non-circular. The colors and materials were less well perceived when using the physical model in comparison to the other conditions, *"I cannot understand the materials form this model … ancient Egyptian buildings did not have marble, so it is limestone"* (participant 27). We hypothesize these observations were mainly due to the particular physical properties of the scaled model of the colonnade. To allow for visual investigation from the top, the model lacked a ceiling, which in turn caused people to observe the length from above. In addition, the columns were 'cut through' at their very top end, which are square. Finally, people perceived the 'external' width including the thickness of the walls, whereas the walk-through view only allowed a view from inside.

We propose that future comparative experiments should have quasi-identical levels of representation abstraction in both the digital renderings as the physical models, and that spatial estimation questions could potentially be fine-tuned by asking participants to also draw the thickness of the walls and ceilings (Figure 3-10.b). Yet we also wish to point out how seemingly trivial issues like opening ceilings or vertically sectioning a building can easily become misconstrued by visitors. As a result, an equilibrium needs to be found between the positive qualities of tangible interaction via physical representations and the actual level of realism that can be fabricated within obvious constraints of financial costs, robustness and historical accuracy. While often absolute realism is wished for, abstraction and ambiguity is a well-known design method to engage users to take responsibility in interpreting its meaning and functionality [Gaver et al, 2003].

3.5.3. Role of Grasping

We believe that grasping a physical model, bringing it closer to one's eye and observing it from different angles facilitates the communication of correct scale and more detailed information. In the graspable-centered sub-condition of *Tang-Phys*, all participants understood the symbolic significance of the story, led to more precise communication of the architectural scale (i.e., width of the colonnade and proportion), and to more accurate estimations of the number of fluted columns and their shapes in the *graspable* sub-condition, particularly compared to the identical sub-condition during which participants could not grasp the physical model itself (i.e., *fixed*).

This evidence encourages further developments in allowing visitors to grasp physical models or replicas for better communication of the tacit knowledge or the finer details of heritage artifacts. However, to enable tangible forms of interaction, graspable models must be equipped with sensors (e.g., touch, orientation) or actuators (e.g., lights, motors) that are subtly embedded almost or wirelessly connected. In addition, such technological interventions should be meaningful, respectful and intuitive to be understood [Nofal et al, 2017.c]. In addition, the technology itself could potentially disturb an immersive experience of the heritage communication. For instance, during our study, some participants were curious to discover the hidden technology driving the installation in the *graspable* sub-condition, probably because of the visible wiring. Furthermore, interactive objects require affordable and robust forms of technology, which cannot be simply stolen or damaged, and thus issues of cost and ease of replacement should be well considered [Marshall et al, 2016].

3.5.4. Role of Material Characteristics

The intrinsic multimodal characteristics of tangible interaction requires taking into account characteristics that reach well beyond the graphical, including aspects such as embodiment, physical abstraction, and materiality (i.e., texture, weight, friction, etc.)

We believe a persuasive part of tangible interaction is its ability to offer participants the opportunity to decipher its affordances through different forms of embodiment, in order to allow them to discover the interactive features as well their potential meaning in forming a historically valid narrative. To entice a sufficient level of curiousness and engagement, this discovery process should be non-obvious yet sufficiently simple that people feel encouraged to explore all the hidden functionalities without frustration. Within our design, we therefore exploited the concept of embodiment, which is considered one of the main attributes of TUIs because it supports learning unconsciously [Bakker et al, 2012]. According to [Kenderdine, 2016], embodiment plays a constitutive role in communicating heritage information when it is entangled through context and environment, which enables visitors to get more involved in historical stories [Kidd, 2017]. We considered several forms of embodiment when designing the *Tang-Phys* condition. For instance, we made a physical representation of the Djoser pharaoh which was able to be moved along a groove representing the Nile River (Figure 3-10.a), embodying his journey along the Nile. The physical representation model showed the space from above, embodying the architectural qualities of flutedness by 3D printing them (Figure 3-10.b). Overall, the small physical model embodied the spatial experience of the colonnade when the model was grasped and viewed on eye-level, so that the columns and small statues appeared as they were ‘in the space’ (Figure 3-10.c).

Likewise, we propose that the concept of physical abstraction plays a crucial role in the imagined potential of more embodied forms of representation, as a crucial difference exists between the abstracted neutral aesthetic of a model fabricated out of white, thick walls in condition *Tang-Phys* versus the more realistically colored stone brick textures on the digital 2.5D models in the other two conditions. Consequently, participants tended to differ in opinion in terms of the ideal level of abstraction, as some *Tang-Phys* participants complained about too much abstraction in the physical model, *"I have a difficulty in imagination … I have to see something in 3D to form a real image about it"* (participant 25), whereas others (from *Touch-Dix*) actually wanted a more abstract form of visualization for the digital renderings: "you can gain a better sense of information if you look at the colonnade from a top view" (participant 41). For some participants, the geometric and 3D-aesthetic of the 2.5D rendering made it look like a 'game': *"it did not look very well … the quality looked a bit (like a) video game"* (participant 7, *Tang-Dix*).

Tangible interaction requires the material construction of objects, making the concept of materiality relevant for both the navigation (input) and the representation (output) modalities, as the power of material characteristics enable heritage visitors to acquire the cultural meanings [Duranti, 2017]. According to [Dudley, 2010], materiality emphasizes the visitor's sensations and personal interpretations of heritage information through the physical objects they interact with. For instance, the texture (i.e., rough versus glossy surface) of the physical model probably impacted how people imagined the spatial qualities of the colonnade, and the materials they imagined the colonnade to be of marble *"a rough colonnade, maybe made out of marble"* (participant 26). The experienced weight and friction of moving the pharaoh along the groove also played a role in the general experience of the installation *"I like it because I can move the pharaoh along the Nile"* (participant 38), and *"with the colors, I prefer this part [navigation] because I interact and touch the statue"* (participant 36) from *Tang-Phys*.

Overall, one could argue an equilibrium needs to be sought towards the average preferences of the public at large in terms of deciding the embodiment, abstraction or materiality. As when too much emphasis is put on the information, the physical object dissolves into meanings [Genoways, 2006]. Yet, the mentioned concepts are also potentially powerful design aspects that could become exploited for more explicit design goals in steering useful forms of tangible interaction. For instance, the actual embodiment of narratives and historical facts could be made more ambiguous to allow visitors to guess their metaphorical meaning, whereas a varying level of abstraction could relate to the corresponding level of historical accuracy of current heritage knowledge. Likewise, heavy or glossy objects could guide the attention of visitors towards more precious or historically valuable aspects of a specific site or objects.

3.5.5. Shortcomings and Limitations

In our study, the experiments were deployed for a relatively short time with a limited number of participants. Due to the corresponding small sample size, the results of the UEQ did not show any significant statistical differences among the conditions. We also realize that the conclusions might be limited to conveying information by ways of tangible interaction that links direct navigational input controlled by users unto locative information that has a metaphorical meaning. At the same time, we believe that most of our findings can be generalized towards many other forms of tangible interactions that are meant to communicate information towards a lay audience.

We used only low-fidelity prototypes in our experimental conditions, which is known to lower the expectations of participants [Claes and Vande Moere, 2017]. This observation also was demonstrated by how many participants expected 'more', particularly in terms of the information that was offered: *"you see only this corridor, but if it is linked to information of these [the nomes], that could be very interesting"* (participant 21) from *Touch-Dix*; as well as in terms of interactive features: *"it would be better if during the interaction, the person in the 3D model gives us some explanations"* (participant 40) from *Tang-Dix*. With regard to the experiment setup, the informative poster was displayed in *Tang-Phys* condition on the large LCD display behind the installation instead of hanging it on the wall in the other two conditions (Figure 3-2. f). This setup might affect the results because the display was larger and placed in a more prominent location, although the chronological analysis (Figure 3-7) does not show more focus on the poster in this condition, but this could be due to the manual observation and analysis. Additionally, due to language barriers, only few families involved their children in answering the questions during the interview and all the internal discussions among families were in their own language. Accordingly, it was challenging to report on the age-related differences in terms of how children understood the symbolic significance and how they comprehended the spatial aspects. Moreover, on busy museum days with large crowds, our installation might not be ideal, as queues could form. It could be ameliorated by choosing a social approach, one that allows people to share their experience with each other. For instance, multiple scale models could be used and light up. Furthermore, according to the concept of participatory museum and connecting visitors [Simon, 2010], we believe that incorporating a TUI in our prototype might well increase the interactions among museum visitors who do not know each other to actively engage and to socially interact, not only among families [Wakkary et al, 2009]. However, due to the limited number of participants and the short time of the experiment, we only observed and mapped the discussion and social interaction among the visitors who knew each other in advance and arrived in groups (i.e., family visits or group of friends). Accordingly, we recommend that the influence of these kinds of installations on social interaction in a museum context should be further investigated.

3.6. Conclusion

In this paper, we conducted a between-group comparative study to investigate how tangible interaction influences the communication of tacit knowledge of built heritage and how this affects the experience of visitors in a real-world museum context. Our three experimental conditions showed different findings regarding the communication of a particular story, which relates a historical journey in ancient Egypt to the physical and architectural characteristics of the entrance colonnade at the Djoser Complex in Saqqara. Our findings indicate how the communication of tacit heritage knowledge in museum environments could benefit from interactive physical models instead of introducing digital 3D models. Digital displays stimulate social interaction among visitors, and enable them to estimate relatively well the internal width of the colonnade and the number of columns. While the physical scale model was better in conveying the symbolic significance of the colonnade, and it was more positively rated in terms of attractiveness and perspicuity. When allowed to grasp the physical model, visitors were also more accurate in estimating the external width of the colonnade, and many of them perceived particular physical characteristics, i.e., the flutedness of the columns.

We concluded our paper with a set of discussion points and recommendations for future research or development of alternative approaches to communicate the meanings and values of heritage. Such as, when combining tangible interaction navigation and representation modalities, an equilibrium needs to be sought between the affordances and the required cognitive effort, depending on the specific focus or narrative of the intended communication. We discussed how the level of realism, physical construction and manipulation features of a 3D scale model influences how people observe and remember architectural qualities. Grasping tangible models proved to effectively communicate correct scale and more detailed information, such as proportions and the shape of columns. Aspects of embodiment, physical abstraction and materiality were also discussed as powerful design characteristics to be exploited for more explicit design goals in steering useful forms of tangible interaction.

Chapter 4:

Nimrud Relief

4

This chapter has been previously published as:

Eslam Nofal et al. (2018.b). "Architectural Contextualization of Heritage Museum Artifacts Using Augmented Reality", *Studies in Digital Heritage (SDH)*, 2 (1), pp. 42-67, DOI: https://doi.org/10.14434/sdh.v2i1.24500

Abstract

Context is crucial for understanding meanings and values of heritage. Several heritage artifacts from recently destroyed monuments are exhibited in different museums around the world. As such contextualizing those isolated heritage artifacts enables museums to communicate architectural and spatial qualities of the original context to their visitors. With the rapid evolution of digital technologies, museums started to incorporate Augmented Reality (AR) to present and interpret their collections in more appealing and exciting ways. AR allows both an enrichment of heritage communication, and also encouragement of interactivity in museums. Through a field study in a real-world museum environment, we investigated how AR enhances the communication of the original context of an isolated artifact from the Nimrud palace in Iraq. We deployed a mixed-method evaluation methodology that led to an effective and engaging communication of the architectural context of that artifact, particularly perceiving and recalling architectural features and spatial dimensions. We conclude the paper with a set of discussion points about how AR positively affects visitors' memorability of architectural qualities, and how it provokes their curiosity to explore more information. We highlight some considerations about AR visualization, such as how levels of embellishment direct user's focus of attention, and which aspects should be considered when using AR abstract visualization to communicate heritage. We outline several design recommendations to overcome current AR usability issues in museums about intuition, freedom of movement, and age-related differences.

4.1. Introduction

Context can be described as an environment or a background that combines various elements or items to create a whole. All types of knowledge are context related [Nesbitt, 1996], as the context is the key to understand any associated knowledge. In architectural heritage, like many other fields, context plays an important role in communicating different meanings and values. Outstanding values of architectural heritage might be attributed to architectural qualities, structural aspects, historical or social significance of monuments and archeological sites.

In museums, visitors are interested to learn about the origin and time period of artifacts. An artifact of importance to heritage may have little or no intrinsic value when it is decontextualized in a museum, as its value arises from the original context [Thompson, 1994]. This context is usually connected to a specific environment that consists of a particular space and a time period. There are three core aspects related to context of heritage. Firstly, architectural context: such as how the artifact was an element of design style or decoration of a particular interior space. Secondly, historical context: such as how the artifact is attached to an important event or a historic figure. And finally, social context: such as how the qualities of the artifact become a focus of spiritual, political, symbolic or other sentiment to a group of people.

It is believed that displacing heritage artifacts from the original location where they were found means that a great deal of contextual information is lost [Thompson, 1994]. This might imply that it could be ideal to keep heritage artifacts in its original context for more effective communication and interpretation of these artifacts. However the case is different when the original context of artifacts is heritage in danger. As such isolated artifacts exhibited in remote museums are considered as of enormous inherent significance for its absolute value and quality. Yet, the value of their architectural qualities and historical significance cannot be communicated unless they are contextualized in some way or form.

In particular, our research focuses on communicating the architectural context of heritage museum artifacts. We are exceptionally motivated by the recent major damage to many cultural heritage sites in Syria and Iraq, such as the sites in cities of Palmyra and Nimrud [Cerra et al, 2016]. Several artifacts (i.e. fragments) from these sites are scattered around the world in different museums. These artifacts are considered as silent witnesses of the value and importance of the recently destroyed monuments. Accordingly, we aim to architecturally contextualize such museum artifacts using digital technologies to raise community awareness and to enable heritage visitors to appreciate heritage in more experiential ways.

During the past two decades, several emerging digital technologies already influenced the way of disseminating and communicating cultural heritage profoundly to lay visitors [King et al, 2016]. Immersive technologies such as virtual and augmented reality create an effective communication with cultural heritage, offering meaningful relationships between heritage artifacts, visitors and context [Reffat and Nofal, 2013]. Augmented Reality (AR) technology allows for superimposed information or virtual objects as if they coexist in the real world [Azuma et al, 2001]. As such, it enables heritage professionals and museum curators to visualize heritage artifacts and to enhance museum visiting experiences [Mohammed-Amin, 2015; Nofal, 2013]. With the rapid evolution of AR technology, museums incorporated AR to present and interpret their collections in more appealing and exciting ways. AR applications provide meaningful insights and wide range interpretation of heritage museum artifacts [Damala et al, 2007]. In contrast to virtual reality, AR enables an alternative way of museum interaction between visitors and museum artifacts by breaking the barrier between virtual objects and physical museum artifacts [Li et al, 2012]. For instance, AR facilitates visualizing and interacting with 3D digitized museum collections [e.g. Mourkoussis et al, 2002; Wojciechowski et al, 2004], enabling visitors to look at artifacts from different points of view. Further, AR enriches the museum visit by revealing the hidden details of museum artifacts such as geometry and color [e.g. Ridel et al, 2014], or even by supporting virtual restoration of partially damaged artifacts [Stanco et al, 2012]. AR has been also used to geo-tag contextual information for guiding and orienting museum visitors [Mohammed-Amin, 2015]. Some museums use AR applications for increasing social interaction among visitors by allowing them to share personalized tags for museum artifacts while exploring the exhibit [Cosley et al, 2009]. Moreover, AR is used for educational purposes in museums in order not only to promote participation and motivation, but also to create an informal and novel learning environment by coupling the virtual space and the physical scenes [Chang et al, 2014; Yilmaz, 2016]. Thus, visitors comprehend the profound meaning embedded in the exhibits through observation, interpretation, and evaluation of the physical artifacts during their visit. Finally, several museums use interactive AR applications as a catalyst for attracting children and young visitors [Jakobsen et al, 2018], incorporating pervasive game strategies to enhance historical content interpretation as well as user engagement [Angelopoulou et al, 2012].

Consequently, we hypothesize that AR is capable of contextualizing heritage museum artifacts and of increasing engagement and memorability of museum visitors. Through a field study in a real-world museum environment, we deployed a mixed-method evaluation methodology to investigate how AR enhances the communication of the architectural context of an isolated artifact. Therefore, we chose a relief from the Nimrud palace in Iraq, exhibited at the Royal Museums of Art and History in Brussels. It is considered as an exceptional museum artifact due to the recent deliberate destruction of its original context.

4.2. Assyrian Relief of a Winged Genius Head from Nimrud Palace

One of the key masterpieces of the Ancient Near Eastern Collections of the Royal Museums of Art and History (RMAH) in Brussels consists of a very well carved relief depicting the head of a genius crowned with three deifying horns, an elaborate beard and headdress, and some remnants of wings (O.1934), shown in Figure 4-1.a. In the exhibition room it is displayed together with a set of other reliefs and artifacts, all originating from ancient Mesopotamia (Figure 4-1.b). Museum visitors are surely astonished by the artistic quality of such 9th–8th century BCE relics, but they might not be aware of its historic value, not to mention the architectural context where it was once installed.

In Spring 1847, the British adventurer and self-learned archaeologist Austen Henri Layard excavated at the site of Nimrud/Kalhu in present Iraq what he labelled *'Room S'* of the Northwest palace of Assyrian king Assurnasirpal II. What he predominantly found and described in his excavation reports, were the many more than life-size reliefs, depicting all sorts of deities, sacred trees, guards (or eunuchs) and the king himself. What he had discovered was one of the grand roofed halls of the in mudbrick adobes constructed palace. The large stone slabs – orthostates – flanked and supported the rough walls all around the interior and were decorated with reliefs which were originally painted and carved by the best craftsmen of the empire. The entire set-up had the purpose to impress the king's subjects and foreign visitors. The entire Northwest palace counted dozens of such rooms and halls; it made the complex one of the finest and most impressive architectural wonders of its era.

(a) *(b)*

Figure 4-1: *The artifact: Assyrian relief of winged genius head from the Nimrud palace; (a) the relief exhibited at RMAH (60 × 64 cm), and (b) a panoramic view of the exhibited relief among other ancient Near Eastern collections.*

Layard shipped a few of these reliefs he found in Room S to the British Museum [Layard, 1849]. However, he did not mention that he had been cutting out as well the heads of some of these relief figures. That was revealed beyond doubt in the 1970's when Iraqi archaeologist re-excavated Room S and rediscovered several mutilated slabs with winged deities. In the light of the aforementioned masterpiece of the RMAH, historic research has revealed the cut out head of slab 28 of Room S was probably given to the English Captain John Hope by Layard as a present, eventually to end up in the RMAH in 1934 [Englund, 2003]. At Nimrud, the remaining slabs were re-erected in its original position during the intensive restoration works in the 1980-90s by the Iraqi Ministry of Culture. Unfortunately, when large parts of the Northwest palace were digitally restored into a 3D model [Paley, 2002], Room S was not included. The main reason for that, the majority of the original slabs were still in situ at Nimrud, and only a few large and a number of small fragments, such as O.1934 of the RAMH, were scattered around the world in multiple collections; making it more difficult to obtain good and complete data to incorporate it in that 3D model. This reality ended in a disaster in March 2015; the not digitally preserved and restored Room S became the focus point for the deliberate destructions of cultural heritage by militants of ISIL. In dramatic video footage slab 28 of Room S is being mutilated with a sledgehammer (Figure 4-2). Ultimately, the extremist would dynamite the entire palace, leaving everything behind in complete rubble and ruins.

The RMAH artifact (Figure 4-1.a) is now the last silent witness of slab 28, an architectural decorative detail once part of a magnificent grand palace hall. Exploring and finding methods to contextualize such an exceptional museum artifact must be determined as a mission.

Figure 4-2: *Deliberate destruction of slab 28 in Room S of the Northwest Palace in Nimrud, Iraq (March 2015)[1]. Note the cut out piece, i.e. the deliberate removal of the head by Austen Henry Layard (most probably in 1847 or 1850).*

4.3. Methodology

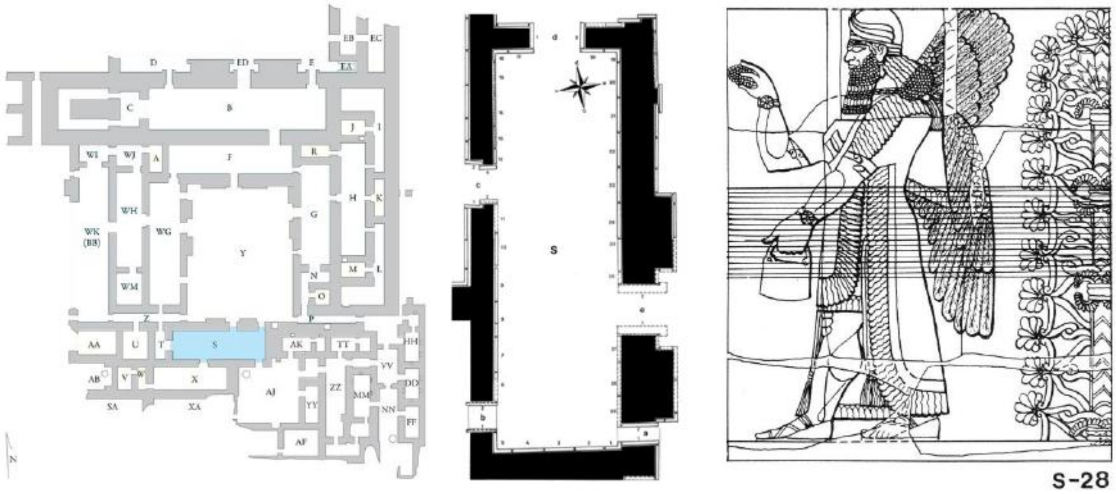
In order to architecturally contextualize the RMAH's artifact from Nimrud palace, we designed and developed an AR application, followed by a mixed-methods evaluation study with 46 museum visitors. In particular, we explore the following questions: (a) how the utilization of AR influences the communication of architectural and spatial context of museum artifacts, and (b) how AR affects the user engagement in a museum environment.

4.3.1. Designing and Developing the AR Application

The collected information about Room S varied in its certainty. From authentic references (i.e. the Nimrud book published by the British School of Archaeology in Iraq [Oates and Oates 2001], and the "Northwest Palace at Nimrud" portal on the Cuneiform Digital Library Initiative website [CDLI, 2018]), we were certain about its location in the palace and its floor plan with the distribution of panels/slabs along the internal walls (Figure 4-3). While other information was yet deficient, such as the height of the room and the different openings, the ceiling structure and the friezes on the walls. For this uncertain information, we estimated the missing spatial and architectural qualities based on the acquired information from other rooms in the palace. These architectural reconstructions were based on the excavated archaeological remains and the scarce original artistic representations of these building complexes. None of the palace rooms and courtyards were preserved in their completeness, where Room S was no exception. Reconstructions are therefore based

[1] A video that emerged on a social media purportedly showing ISIL fighters militants bulldozing the ancient Assyrian city of Nimrud (source: Chanel 4 News on YouTube: https://www.youtube.com/watch?v=wGiY7ZDKZSE on April 12, 2015)

on a broad understanding of the Assyrian construction practices witnessed all over the Northwest palace. According to these uncertainties, we decided to digitally reconstruct Room S in an abstract visualization using SketchUp and Unity 3D (Figure 4-4).



(a) *(b)* *(c)*

Figure 4-3: *Collected information from historical references about the original context [CDLI, 2018]: (a) floor plan of the Nimrud Northwestern Palace, (b) floor plan of Room S, where the artifact was located, and (c) the complete drawings of the slab (S-28) where the artifact was part of it.*

The abstract visualization of Room S was based on a specific design rationale. First, we intentionally designed the Room S as a semi-transparent in order not to fully isolate visitors from the actual museum environment, avoiding any possible risk to the priceless surrounded artifacts. Second, the salient architectural features (Figure 4-4) such as the reliefs' drawings, roof beams and tiles were visualized in a cyan color to stand out. An abstract Assyrian pattern was used to represent the fresco friezes along the walls and the archways which have occasionally been discovered by archaeologists in the palace complex as decoration above the stone orthostates. As little of the original graphics of the frescos from Room S is known for certain, the choice was made to stylize a simplified frieze inspired by alike Assyrian art.

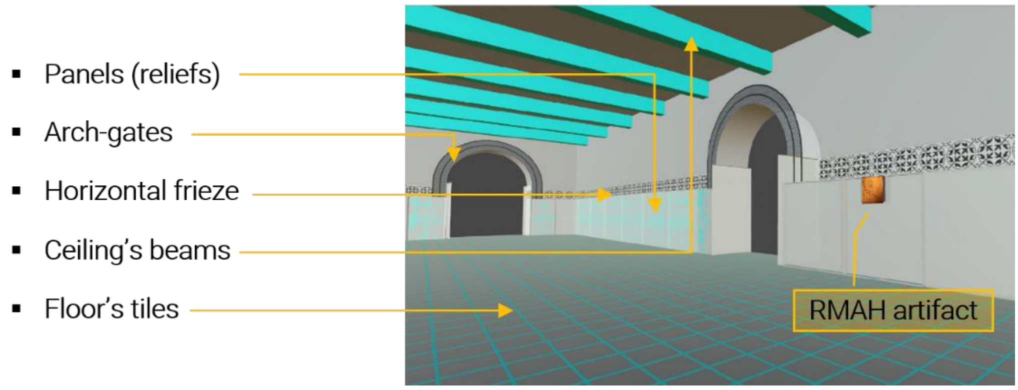


Figure 4-4: *Digital reconstruction of Room S in an abstract visualization using SketchUp and Unity 3D, showing the original location of RMAH artifact, and the intended architectural features to be communicated.*

Unity 3D software was used with Vuforia SDK library to build the AR application. For tracking aspects, 2D image marker was chosen for the development phase. A high-resolution image of the artifact was taken and uploaded to Vuforia as an image target, to be part of the generated Unity package by Vuforia. The image target was scaled and repositioned to its original place in the virtual Room S. The project then was compiled into an iOS project, imported into Xcode and run on a smartphone (i.e. iPhone 6 Plus) for testing in the lab on the artifact printed image, and then on a tablet size (i.e. iPad Air 2) for evaluating the application on the actual artifact at the museum[2], as illustrated in Figure 4-5.

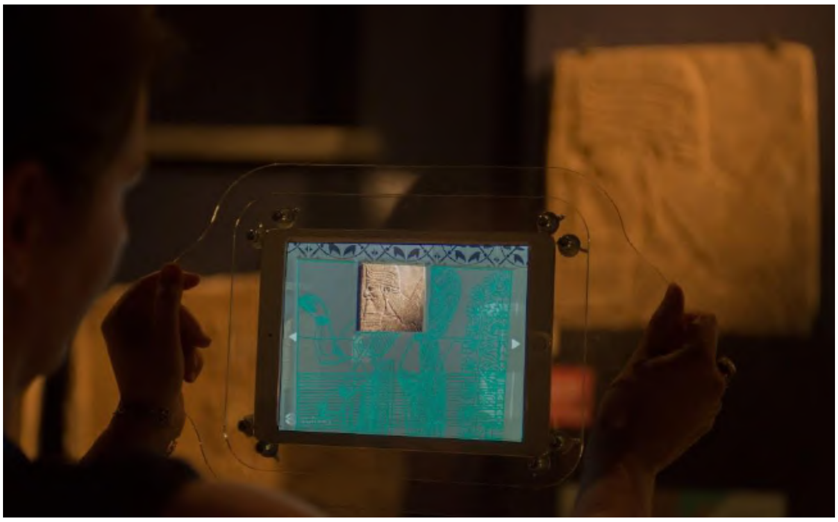


Figure 4-5: *Contextualizing the original context of the artifact using AR application by pointing the tablet's camera to the artifact.*

Lastly, we designed and laser-cut a Plexiglas case for the iPad, so that participants could hold the tablet without accidentally touching or covering up the screen with their hands, shown in Figure 4-6. It was also intended to be more secure and more robust for such a device using in a museum for different age groups of visitors (i.e. children, inexperienced or elderly people).

(a) *(b)*

Figure 4-6: *Custom-Designed tablet case; (a) a participant using the application with the iPad inserted into the case, and (b) the case allowing a group of participants using the application and looking at the screen.*

[2] A video illustration of the AR application is available on: https://vimeo.com/336831335

4.3.2. Evaluation Methods

The evaluation study deployed a mixed-method methodology. Museum visitors were invited first to a *Conventional Visit* of the artifact by looking at the relief and probably reading the labels beside it (i.e. provided by the museum in three languages: French, Dutch and English). Conventional Visit was followed by a short interview to evaluate what they learned and whether they were able to contextualize the artifact. Subsequently, participants were invited to an *AR Visiting Experience* by handing them a tablet and asking them to start from a certain location (i.e. approximately two meters far from the physical object) and to point the tablet's camera towards the artifact to start interacting with the AR application. Their interaction was observed, as they were allowed to look around or to move towards the artifact. Thereafter, we invited them to partake in a semi-structured interview that was combined as well with sketching task of the architectural features of Room S and a user experience questionnaire.

4.3.2.1. Pre-task interview

The pre-task interview, providing demographic information, aimed to evaluate what the knowledge participants gained from the Conventional Visit and how they imagined the architectural context prior to their AR Visiting Experience. We asked our participants about what they learned from their visit and how they imagined the surroundings of the object (e.g. where was it located? was it a standalone artifact or was it a part of a bigger entity? how did the space look like?).

4.3.2.2. Observation

During AR Visiting Experience, all the interactions were video-recorded, observed and manually analyzed in an Excel spreadsheet. The level of user engagement was derived by the duration of their interaction, their apparent focus of attention while interacting and their social interactions with other person(s) nearby. Furthermore, we manually noted the 'angle of view' for each participant while interacting with the AR application from the video recordings. We then graphically labelled the 'angle of view' in two phases: (a) as an *Initial Interaction* to evaluate whether and how people found the application intuitive to use, and (b) as a *Guided Interaction* after advising participants to look around in order to evaluate whether and how the architectural context is communicated. Their tilting angle was also noted to observe whether they looked down to the floor or looked up to the ceiling. The movement of the participants was also observed and noted, such as whether they moved right, left, or towards the physical object while holding the tablet.

4.3.2.3. Semi-structured interview

After interacting with the AR application, participants were invited to partake in a semi-structured interview that was audio-taped, and which focused on revealing the comprehension of the original architectural context, particularly the aforementioned architectural features and the spatial perception of Room S. More questions were then asked to open up the interview towards more qualitative answers, such as participants' impression of using such technology in museums (e.g. what they liked, what they disliked and why).

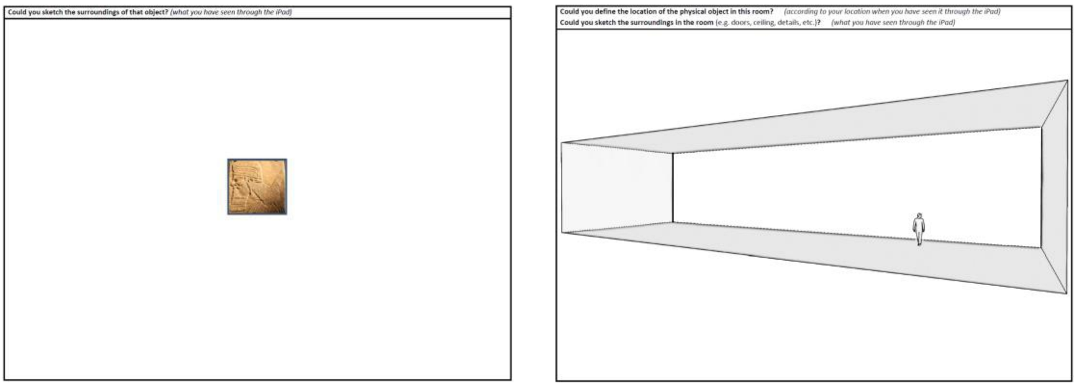
Answers of the interviews were then manually analyzed using an Excel spreadsheet that contains the different aspects of communicating the architectural context, such as how they described Room S and which architectural features they remembered, also averages and medians of estimated dimensions were calculated. Furthermore, participants' quotes from the interview were manually transcribed and then categorized into: what they learned, why they liked it, and their suggestions and dislikes, as shown in Figure 4-7.

(a) *(b)* *(c)*

Figure 4-7: *Extracting quotes from interviews' transcripts: (a) what they learned from this experiment, (b) why they liked this experience, and (c) what they disliked and their suggestions for improving the experience.*

4.3.2.4. Sketching

We also used sketching as a complementary method to reveal how participants remembered the architectural context. After their verbal descriptions of Room S during the interview, they were requested to sketch the appearance of Room S (e.g. shape and elements, etc.) using two papers, one in two dimensions for the close surroundings of the artifact on the same wall (Figure 4-8.a), and the second in three dimensions for a bigger image of the entire room where the artifact was located (Figure 4-8.b).



(a) *(b)*

Figure 4-8: *Sketching the architectural context of the artifact; (a) 2D sketch paper for the close surroundings of the artifact on the same wall, and (b) 3D sketch paper for a bigger image of the entire room where the artifact was located.*

From their drawings, we manually extracted which of the five architectural features (see Figure 4-4) they remembered and graphically reproduced. We then compared the extracted features from sketching to the mentioned features from their verbal description. More details were also extracted from their drawings, such as whether they drew the wing(s) of the genius, his body or how other figures on the adjacent reliefs stand in relation to our museum artifact.

4.3.2.5. User experience questionnaire

The interview was followed by a concise user experience questionnaire that allowed participants to express their impressions or attitudes that emerged when they interacted with the AR application. It contained 9 items to measure how that the application was enjoyable, inventive, good, easy, motivated, efficient, attractive and informative. The items are scaled on 7 points Likert scale from -3 (representing the most negative answer) to +3 (representing the most positive answer, when 0 is a neutral answer.

4.3.3. Evaluation Study

The evaluation study commenced with a low-fidelity test at our research lab with only a few number of participants, which was followed by a one-day pilot study in the real museum environment. Thereafter, we carried out the actual study during approximately two weeks. All participants signed an informed consent form to confirm that they voluntarily participated and that the results of this research can be used only for scientific purposes.

4.3.3.1. Pilot study

Our one-day pilot study in the main exhibition room of the Near-Eastern collections at RMAH aimed to reveal usability issues in an ecologically valid context, such as whether lay museum visitors could intuitively understand how to interact with the AR application. Here, each participant was introduced by a brief explanation about the exhibited object (i.e. historical period) and the purpose of interacting with the AR application (i.e. to explore the original architectural context of the object). The pilot-study included 10 participants, who participated individually or in group, including couples and groups of family visits.

4.3.3.2. Actual study

Based on the results of the pilot study, several modifications were implemented, such as: 1) adding an animated illustration as a popup in the application (Figure 4-9) to stimulate participants to look around and see the entire Room S when they look at the artifact for more than 7 seconds without rotating, and 2) changing the transparency of the digital reconstruction to be more opaque for better visualization of the architectural features. The final study was deployed at different times to maintain ecological validity (i.e. mornings and afternoons) over a total period of two weeks to reach varied types of museum visitors (i.e. local and international visitors with different age groups).

(a)

(b)

Figure 4-9: *Animated illustration that pops-up to participants to stimulate them to look around when they look at the artifact without rotating: (a) a close-up to the pop-up, and (b) the illustration pops-up to one participant.*

4.4. Results

The final study involved a total of 26 participants, who participated individually (15) or in groups (11) with a total number of 46 museum visitors. They form disproportionate user groups of museum visitors, as they varied in gender (i.e. 22 males and 24 females), age range (i.e. 8 children, 3 teenagers, 29 adults, and 6 elderly), and the purpose of their museum visit (i.e. 5 family visits, 6 local tourists, 13 international tourists, and 2 museum staff member).

We categorize our results into two sections: (a) how AR experience enabled participants to contextualize the artifact into Room S in terms of the architectural features and the spatial dimensions, and (b) the usability of AR experience and how it engaged participants (i.e. museum visitors).

4.4.1. Contextualizing the Original Architecture

After the Conventional Visit, participants who read the text label could understand the general information about the object, such as it was a relief from Nimrud's North-west palace and it was from the Neo-Assyrian period. Most of participants (20, N=26) assumed that the object was part of a bigger relief, but they could not imagine the architectural context of the space where the object was located.

On the contrary, after the AR Visiting Experience, their perception about the context changed, *"I learned that the piece was located in a palace, it seems to be a part of a larger relief"* (participant 9). Some even compared it to their Conventional Visit, such as *"it is very insightful to see it in a bigger picture than just this little piece surrounded by many other things"* (participant 17), and how it positively affect their perception about the larger context *"when I see just a small part, I cannot imagine how it looked in the past and what it was, but now it is very interesting to see how it looked in general, not only a small piece … very good for museum visitors"* (participant 18), and *"it is really cool because it gives an impression about the plausible context, which is often neglected. Somehow one does not imagine the rest of a piece in a museum"* (participant 25).

From their verbal description of Room S, we extracted the different architectural features they remembered. Most of the participants (20, N=26) described Room S as a large rectangular space, including many other reliefs on stone panels against the walls, they also mentioned that there were some arched gates connecting Room S with the adjacent spaces. 15 participants (N=26) mentioned the horizontal frieze above the reliefs consisting of an Assyrian pattern. While participants seemed to less focus on ceiling's beams and floor's tiles; only 9 and 7 (N=26) mentioned them respectively.

It is also worth mentioning that when we invited the participants to sketch the surroundings, more information was revealed than from their verbal description. Figure 4-10 shows a comparison about the different architectural features of Room S between participants' sketching and their verbal description.

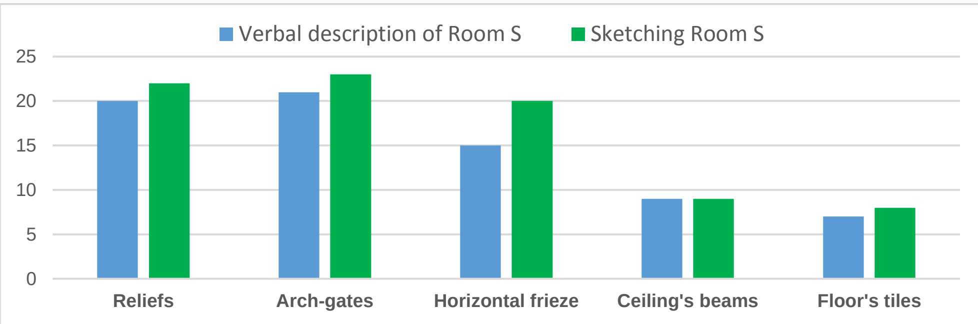
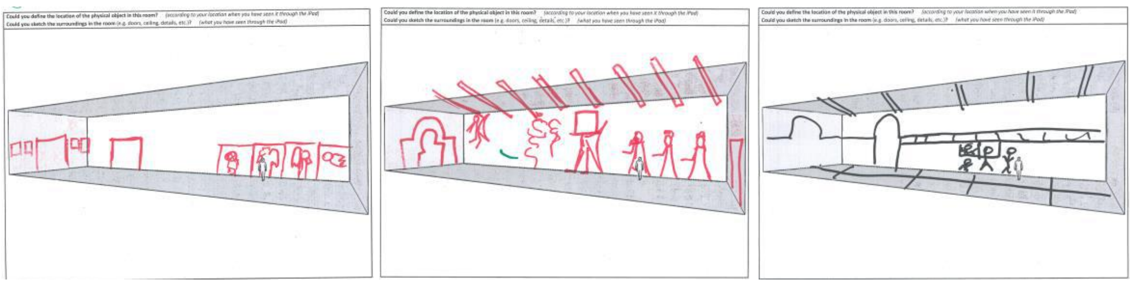


Figure 4-10: *Participants' description of the different architectural features of Room S from their verbal descriptions (in blue) and from their sketching (in green). The Y-axis indicates the number of participants describing the corresponding architectural feature.*

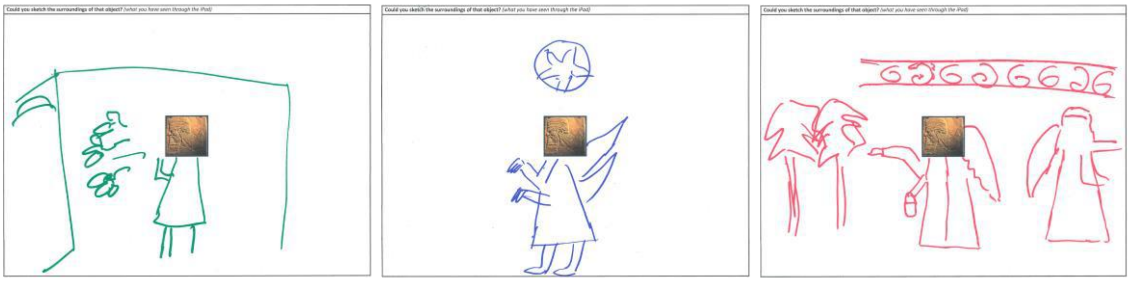
We divide the results of participants' drawings into 3D sketching that focused more on architectural features and 2D sketching that focused more on embellishment. Figure 4-11 shows samples of participants' sketching for the different levels of recalling these architectural features. For instance, the location of the physical artifact in Room S and how it relates to other panels and reliefs, sketched by 22 participants (e.g. Figure 4-11.a, 3-11.b and 3-11.c). Other architectural features such as the arched gates were sketched by 23 participants, and the horizontal frieze was sketched by 20 participants. Whereas only 9 participants sketched the ceiling's beams and 8 participants sketched the floor's tiles. This lower amount of sketching the beams and the tiles might well be the result of only few participants looked up and down during their interaction.



(a) *(b)* *(c)*

Figure 4-11: *Samples of participant's sketches who focused more on the architectural features: (a) sketching the different panels corresponding to the location of the physical artifact (participant 6), (b) sketching more architectural features such as the arched gates and the ceiling's beams (participant 14), and (c) sketching the five architectural features discussed above including the horizontal frieze and the floor's tiles (participant 10).*

In addition to recalling the architectural features, sketching the 2D paper revealed also more details about the embellished drawings that participants perceived and remembered. For instance, 22 participants (N=26) drew the completion of the genius body (e.g. Figure 4-12.a, 4-12.b and 4-12.c), 13 participants recalled that the relief is for a winged genius, and they accordingly drew the wing(s) of the genius (e.g. Figure 4-12.b and 4-12.c), while only 4 participants recalled that the figures were mirrored in the different panels (e.g. Figure 4-12.c).



(a) (b) (c)

Figure 4-12: *Samples of participant's sketches who focused more on the embellishment: (a) sketching the body of the genius (participant 22), (b) sketching the body with the genius's wings and a representation of the frieze above (participant 24), and (c) sketching the body with the wing and how it related to the other drawings on the side panels (participant 20).*

Spatially, participants described Room S as a large rectangular space. Their estimation of its height varied from 4 m to 10m with an average of 6.3 m (median is 5 m), which is very close to the actual height of Room S in our digital reconstruction (6.5 m). Their average estimated width of Room S was 8.7 m (median is 7 m), which comes also close to the actual width (9.5 m), varying from 5 m to 20 m. While participants varied in their estimations of the length of Room S from 10 m to a relatively overestimations towards hundred meters, with an average of 35.8 m (median is 16.5 m), the actual length is 30 m. Table 4-1 summarizes the actual and estimated dimensions of Room S, calculating the error range.

Table 4-1: *Actual and estimated dimensions of Room S.*

Dimensions of Room S	Actual dimensions	Estimated dimensions (avg.)	Error range
Height	6.5m	6.3m	-3%
Width	9.5m	8.7m	-8%
Length	30m	35.8m	+19%

Since spatial estimations are very close to the actual dimensions as illustrated in Figure 4-13. Error range of average estimating Length of Room S is relatively higher than the error range of estimating both Height and Width, as indicated in Table 4-1. This mis-estimation of Length might well be a result of the rectangularity of Room S, especially because participants were positioned of the way towards the edge. Rectangularity produce substantial illusion, as more rectangular rooms consistently are estimated as larger than less rectangular rooms of equal size [Sadalla and Oxley, 1984]. We then could make a potential generalization of these results that AR could be an appropriate medium to communicate the spatial dimensions of square or less-rectangular spaces that communicates heritage lost context.

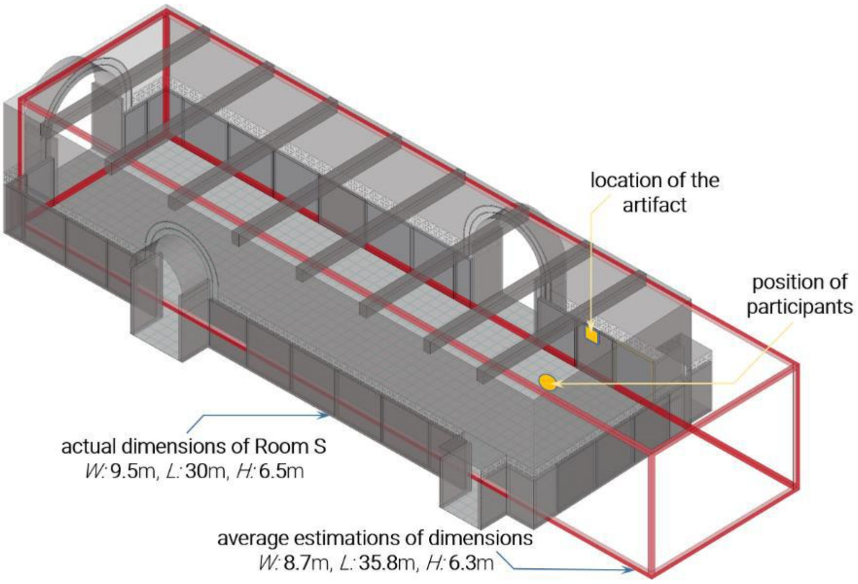


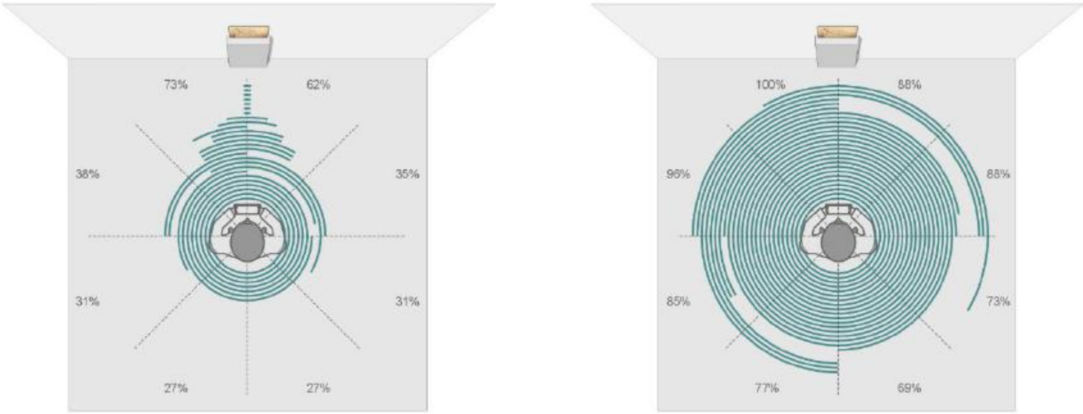
Figure 4-13: *The participants' average estimations of dimensions (in red) compared to the actual dimensions of Room S.*

4.4.2. User Experience

We report in this section on the user experience in terms of the apparent focus of attention during interaction, participants' answers of the user experience questionnaire, and their forms of engagement and appreciation.

4.4.2.1. Focus of attention

Participants focused their attention on varying angles of view during the interactive exploration process. Figure 4-14 shows a top view of a participant holding the tablet, demonstrating the focus intensity for looking at the different angles of view during the interaction. Consequently, more arcs (i.e. number of participants) can be noticed in the angles in front side, close to the physical exhibited artifact, while only a limited number of participants (i.e. 27%) looked at the back side of Room S during their Initial Interaction (Figure 4-14.a) despite of the animated pop-up. Whereas, after the Guided Interaction (Figure 4-14.b), more participants looked at the other sides of Room S (i.e. around 90% at the left and right sides, and around 70% at the back side). In both Initial and Guided interaction (Figure 4-14.a and b), most people looked at the left side of Room S more than the right side. This might well be the result of the position of participants and the location of the artifact in Room S (Figure 4-13), as the bigger part of the space can be seen from the left side. It might be also a result of the physical museum environment, as on the left side some other Assyrian artifacts were exhibited that might stimulate participants to look more towards left (Figure 4-1.b).



(a) *(b)*

Figure 4-14: *Participants' focus of attention in terms of 'angle of view' in their AR experience (each green arc represents the total angle of view of one participant, indicating the percentage of participants for each angle): (a) is an Initial Interaction, while (b) is a Guided Interaction after telling them that they can look around.*

When we compared the angles of view to the perception of the architectural features, we noticed that participants who restricted themselves to a limited angle of views, described less architectural features during the interview and in their sketching. We also noticed that participants who had a limited angle of view during their Initial Interaction, participated individually. While other participants who had 360° interaction, most of them participated in groups. We therefore hypnotize that participating in groups encourages visitors to explore more by looking around, having an inclusive view of Room S.

Further, we observed that only few participants looked up (8, N=26) or down (8, N=26) during the interaction. This might well be the cause of less perception of ceiling's beams and floor's tiles (Figure 4-10). With regard to the movement of participants during the interaction, we noticed that most of them (18, N=26) were steady, they did not move. While other participants (8, N=26) started to move a few steps, mainly forward and to the left side. One of them even moved until he reached the physical object and then moved all over the space. Comparing the movements of participants around the space to their answers during the interview, we noticed that those who moved around perceived more architectural features from their verbal descriptions and from their sketching as well.

4.4.2.2. User engagement

In general, individual participants spent less time interacting (112s, avg.) in comparison to groups of participants (140s, avg.), as the discussion between group members encouraged them to look around and to explore more. We also noticed that children (i.e. <12 years old) spent more time in their interaction (140s, avg.) than particularly elderly (95s, avg.). Beside the time of interaction, elderly (i.e. > 65 years old) seemed to appreciate the AR experience less (i.e. 2 old participants did not like it); *"we are too old for this kind of stuff"* (participant 21). Elderly participants preferred to focus their attention on the physical object rather than looking at the context through a display *"I don't like it, I would like to see the pieces in front of my eyes … that's for me the real thing, I would like to admire the object directly"* (participant 3). Whereas children liked the AR experience much more because they found it attractive, a mother with three kids commented that *"it is very difficult to attract children, and you can see how they paid attention, otherwise they would just look around for one or two seconds"* (participant 14). Figure 4-15 shows the number of participants for the different levels of appreciation.

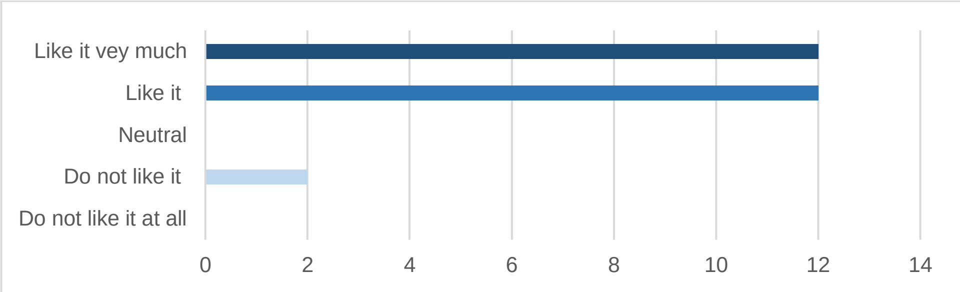


Figure 4-15: *Level of appreciation to the AR experience, showing the number of participants for each level.*

4.4.2.3. User experience questionnaire

The results of the user experience questionnaire (Figure 4-16) convey the usability of our AR application and the participants' attitudes toward using it. Most of the participants (24, N=26) found the application good; *"it is very good, especially for children and people who do not know the matter that well … they can really visualize how these fragments would have looked like in rooms or buildings"* (participant 10). Likewise, 24 participants found it inventive, one participant even commented that: *"I needed some time to get familiar with the device, it was too much of novelty"* (participant 25). Participants (23, N=26) also agreed that the application was motivating them to visit the object and interact with it; *"to be honest, if I was walking to this room, I probably not stop at that object because there are many things to look at"* (participant 7). Their motivation even extended beyond their museum visit; *"after this experience, I would like to go there and to see this piece onsite"* (participant 22), that participant most likely did not know that the remnants of the original palace were recently destroyed. 22 participants (N=26) considered it attractive as well, particularly children and young museum visitors, validating the results from the previous section. Participants (23, N=26) believed the application is informative; *"in this museum, it is really hard to interpret the objects … these are here just pieces of stone exhibited against the walls … but actually through the application, it is quite important to know that they were part of a big building"* (participant 10). However, more participants disagreed with the ease and clarity of the application. It seemed that unclarity issues are resulted from the abstract visualization, for instance 3 participants found it unclear; *"it was not absolutely clear what you wanted to communicate because it (panels) was a bit transparent"* (participant 2), who continued *"this kind of application must not distract from looking at the object itself"*. Moreover, one participant thought the application is difficult because (s)he tried to flip the tablet several times, so the visualization was a bit laggy *"when we hold the tablet and we move, it is like we are in a boat"* (participant 22). Another participant could hardly see the tablet's screen which was held by his group-mates, who were relatively shorter than him. He commented that *"it is a bit hard tool to use, particularly in a group setting"* (participant 7).

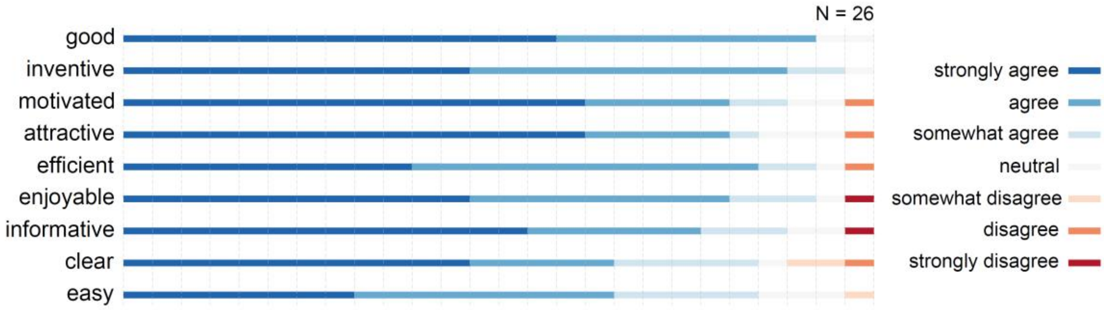


Figure 4-16: *Results of the user experience questionnaire; each row shows an item scaled from strongly agree (blue) to strongly disagree (red), while each cell represents the answer of one participant.*

4.5. Discussion

In this section, we discuss the implications of the previous results with relevance to future research or potential further development of AR applications that communicates heritage in museum environments. We explain the qualities of using AR in museums, such as how it positively affects visitors' memorability of architectural qualities, and how it provokes their curiosity to explore more information. We highlight some considerations about AR visualization, such as how levels of embellishment direct user's focus of attention, and which aspects should be considered when using AR abstract visualization to communicate heritage. We outline several design recommendations to overcome current AR usability issues in museums about intuition, freedom of movement, and age-related differences.

4.5.1. AR Communication in Museums

4.5.1.1. Usability issues

AR navigation in museums seems to be insufficiently intuitive for lay visitors. Part of our AR experience was meant that participants should look around during their interaction and to look at Room S from different points of view. However, results show only few participants (i.e. 27%) looked at the back side during their Initial Interaction despite of the animated illustration that provokes them to look around. In terms of usability, AR interaction was less intuitive because of the time needed to start navigation and looking around *"I needed some time to get familiar with the device, it was too much of novelty"* (participant 25). As a possible solution, we provided them with a kind of verbal instructions to look around that enhanced their AR experience. For other participants who are used to touch screens, they assumed to have more functions on the tablet display, such as rotating and zooming *"I would like to zoom and see more details … if you have an iPad, you should be able to zoom or press a button for more information"* (participant 1). Consequently, we recommend that AR experience in museums should consider some kind of instructions to overcome the usability issues. In a museum environment, gaming strategies or honeypot effect might be suited where visitors interacting with the application passively stimulate other visitors to observe, approach and engage in an interaction [Wouters et al, 2016].

4.5.1.2. Freedom of movement

Allowing museum visitors to freely move during their AR experience should be carefully considered. AR technology is considered as an immersive experience [Dunleavy et al, 2009] because users whenever hold the tablet, their attention is drawn to the screen. In our study, the environment around the artifact was relatively spacious, allowing visitors to move forward and backward and to look at the artifact from different points of view. Results show how this freedom of movement led to better communication of the architectural qualities in terms or perceiving and remembering the architectural features. While in other scenarios, visitors' freedom of movement might be quite risky because of the priceless artifacts that are exhibited in the vicinity, visitors might hit them inadvertently. Because freedom of movement during AR experience causes a better communication of architectural context, we recommend that museum visitors are able to walk around. Yet, the physical surroundings should be carefully considered when using such AR experience in a museum environment. For instance, dense and narrow spaces should be certainly avoided.

4.5.1.3. Curiosity

Using AR in museums stimulates curiosity of visitors, they realize new insights that causes an exploration process of information that is not necessarily available within the AR environment. It is suggested that AR experience in museums should encourage visitors to explore more information about the museum artifacts [Tillon et al, 2011]. But the issue is whether this information should be accessible or not. As providing the desired information will solve the appetite for visitors to stay informed, but doing so will also inevitably brake the immersion, as it will need to be shown via images, text or audio. In our study, because of the low-fidelity prototype, many participants expected 'more', particularly in terms of the information that was offered: *"you can use the iPad and at the same time a narrator could talk to you about the palace and the piece"* (participant 24) and *"if I could select an object that I am interested in, and get more information"* (participant 23); as well as in terms of interactive features such as *"the movement or the simulation of persons from the past"* (participant 26). Accordingly, we recommend that AR should be used in museums to provoke different forms of curiosity about the architectural, historical or social contexts. This quality should be further investigated and benchmarked versus more common informative approaches.

4.5.1.4. Age-related differences

We also believe that current AR museum experience does not suit well all age groups of visitors. Based on our results, AR seems to be less appreciated by elderly people; *"I am an old man, I prefer books or even to see a good video"* (participant 11). Also, disliking the AR experience arises only from elderly people (Figure 4-15). On the other hand, younger participants, particularly children, appreciated the application more and the whole experience achieved to attract and motivate them to interact and to acquire the knowledge in an indirect manner. Previous HCI studies on effect of user age show that small screen sizes and complexity cause more difficulties for elderly people in browsing smartphone interfaces [Al-Showarah et al, 2014]. Elderly people also may have decreased capabilities for interfaces that require motor actions from neck and face [Hands and Stepp, 2016]. From our evaluation study, we noticed that elderly participants looked up and down less during their interactions. Accordingly, we propose AR museum experience should take into consideration age-related differences of visitors. For instance, less complex interfaces and larger screens should be used, and also target artifacts should not be neither relatively low nor high to decrease the required neck motor actions.

4.5.2. Memorability

The use of AR in a museum environment positively affects the memorability of visitors. In particular, it influences how they perceive and recall architectural features and spatial dimensions. Previous research [Juan et al, 2014; Hou and Wang, 2013] also shows that AR is more effective in retaining the information in the short-term memory, as it enhances spatial comprehension and it improves cognitive transformation.

Memory is a cognitive process that is crucial for the appropriate learning or understanding of any knowledge. AR museum studies demonstrate that AR enhances visitors' understanding of the meanings of museum artifacts (e.g. [Tillon et al, 2011]), and thus their memory. In our study, although most of participants have read the text-labels, only few of them remembered what was written when we asked them what they learned from their first Conventional Visit; *"when I read something like that (text labels), it does not stay in memory very long"* (participant 2). However, after the AR Visiting Experience, our results show how they remembered several architectural features of Room S in addition to the drawings' details. Our findings also show how AR experience enabled participants to perceive and to accurately estimate the dimensions of Room S as illustrated in Figure 4-13. Yet, participants did not perceive nor remember well some architectural features, such as beams and tiles. This might well be the result of only few participants looked up and down during their interaction.

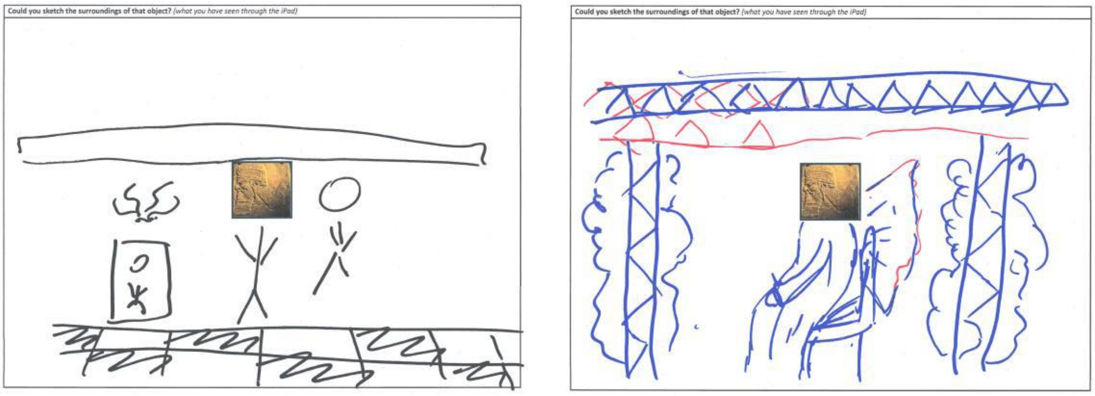
Therefore, we recommend that AR could become an effective medium to convey the architectural features and spatial dimensions of museum artifacts and their related contexts. Nevertheless, further investigations are also encouraged to evaluate whether this short-term memory might well lead to longer-term memory. As heritage communication should not be only about remembering the information for a short period of time.

4.5.3. Levels of Embellishment

The visitor's focus of attention is directed by the levels of embellishment in AR visualization. In this study, the functional aspects of Room S were visualized in a relatively low embellished level. However, our visualization of Room S comprised a higher level of embellishment for the detailed drawings of the different reliefs.

During the evaluation study, we were surprised by the amount of embellished details that participants recalled and even sketched. Their verbal description and their sketching of the original context were diverted more towards the fine details of the drawings, such as the wing of the genius and other surrounded drawings (e.g.

Figure 4-17.b) than the functional aspects (e.g. Figure 4-17.a). One participant was asked during the interview whether he remembered any functional aspects in the ceiling or the floor, but he commented that *"I was more interested in the drawings"* (participant 20). Literature also proves that people tend to better remember the content of embellished visualization [Borgo et al, 2012], because embellishment is a cognitive difficulty, causing more cognitive processing. That means the more embellished the visualization is, the more difficult to be understood but the better to be remembered.



(a) *(b)*

Figure 4-17: *Two samples of participant's sketches of the close context: (a) for a participant who focused on the functional and architectural aspects by sketching the floor, horizontal strip representing the frieze, an abstraction of the gateway and abstract figures (participant 10), while (b) is for a participant who focused more on the embellished details by sketching the body with the genius's, more detailed representation of the horizontal frieze, and how it related to the other drawings on the sides (participant 2).*

Accordingly, we recommend that the levels of embellishments in AR visualization should be mapped to the user's focus of attention. As if we would have embellished the room too much, the focus point of the spatial qualities might have become diminished. Yet the choice of the different levels of embellishment might well depend on the specific focus of the intended communication. For instance, when it is expected that museum visitors should focus on the drawings, then a more embellished representation for the drawings might be more suited. Nevertheless, an equilibrium needs to be sought because more embellished AR visualization would become overwhelming or difficult to be understood.

4.5.4. Abstract Visualization

Aspects of transparency and choice of colors affect how users appreciate AR abstract visualization. Although all participants understood the original architectural context of the artifact and correctly described the prominent architectural features of Room S, even so 11 participants (N=26) preferred to see a more realistic view instead of the abstract visualization; *"I would like to see the real colors of paintings (reliefs)"* (participant 2). That might be because visitors are used to realistic visualization *"because we are so used to things like videogames and similar things, which is so realistic. I compare it to that and I think it is probably too static"* (participant 2).

The semi-transparency of the visualization seemed to be one of the reasons that made participants less appreciated the abstraction *"it was not absolutely clear what you wanted to communicate because it was a bit transparent"* (participant 2). As it might have lowered user's level of immersion *"if it is not transparent, I would feel really inside the room"* (participant 19). Moreover, the choice of colors seemed to negatively affect the AR experience with the abstract visualization*; "I dislike that you just could see that small piece (relief) in colors, but the rest was like in blue lines"* (participant 17). In particular, they claim that the choice of cyan color made the abstract visualization less preferred *"it could be done graphically better … still contemporary, but maybe brownish color would be different. I really do not need very realistic computer-like environment view, but just different colors"* (participant 16). More specifically, the use of high-contrasting colors (i.e. cyan) to highlight specific features (i.e. tiles and beams) seemed to hinder the communication of other features visualized in lower contrast *"the visualization caused a memory problem because of the low contrast. Black and white (frieze) stayed in memory, but the light grey did not because of the diffusion, and the green (cyan) grid captured the attention over the reconstruction (light grey)"* (participant 22).

On the other hand, we believe that abstraction holds several advantages in AR experience, such as how to visualize uncertain information. As realistic visualization might give museum visitors false impression of certainty *"if the room was reconstructed as it could have looked, too many people might think that is exactly how it looked like"* (participant 25). For instance, any more detailed information to the reconstruction of Room S would be guessing, because we know how the basic outlines of the drawings were, but maybe there were some other features in the room itself that we do not know. In this case, many visitors might think that it is exactly how Room S appeared like, however it is only how it could have looked.

Consequently, AR abstract visualization might be suited for communicating uncertain heritage information. As such, we propose that level of abstraction in AR visualization should correspond to the level of information certainty. Yet, aspects of transparency and choice of colors should be carefully considered in the visualization design. For instance, all the required features to be communicated, should be visualized in high-contrasting colors compared to other features.

4.5.5. Sketching as an Evaluation Method

Sketching is a suitable evaluation method to capture the perception and memorability of contextual information, such as architectural features. As such, it can be used in other studies that focus on the communicative effectiveness of qualities that relate to space.

Although most participants initially hesitated to sketch the surroundings due to a sense of social embarrassment or self-perceived poor drawing skills, almost all participants eventually sketched the surroundings of Room S. Participants also tended to recall more architectural features while they were sketching as illustrated in Figure 4-10. Furthermore, sketching obviates language concerns between researchers and participants. For instance, the horizontal frieze was mentioned in the verbal description by only 15 participants, while it was sketched by 20 (N=26). Perhaps also when they started to draw the panel, the inclusive visual image would be clearer in their minds. It only might more naturally access particular parts of the brain, and thus memory.

Accordingly, we propose that sketching should be considered as a complementary evaluation method for future experiments that communicates heritage in museums. Yet, further studies are encouraged to investigate whether sketching could also stimulate visitors to report on other types of heritage information (e.g. cultural and social), and whether sketching should be always accompanied with verbal description or it can be a standalone evaluation method.

4.5.6. Shortcoming and Limitations

In this study, we realize that the conclusions might be limited to convey information via an AR application that was intended to communicate the original context of heritage museum artifacts. For instance, we deployed the experiment for a relatively short time with a limited number of participants who had different backgrounds with varying degrees of expertise. The chosen artifact was located originally at a museum exhibition room, that room was quite dark. At the same time, we believe that most of our findings and discussions can be generalized towards many other forms of AR that are meant to communicate heritage information towards a lay audience.

Concerning estimating the dimensions of Room S, the medium and techniques we use (i.e. mobile AR) to represent the space might not be the only factor that affects the spatial cognition, but also people generally differ in the way how they perceive spaces and accordingly how they estimate spatial dimensions. For instance, architects might be well skilled in perceiving spaces and they are very familiar with estimating dimensions compared to other museum visitors. As we did not normalize the participants according to their professions or backgrounds, we recommend that these aspects should be further investigated to which extent they affect the spatial cognition of museum visitors.

Moreover, on busy museum days with large crowds, AR might not be ideal, as queues could form *"I like the experience, I think it is a good idea, but I wonder if you have enough iPads for people to actually use"* (participant 9). One could argue that commercializing the application could resolve this issue, including much more museum artifacts, which visitors could use for any of the master pieces at the different museum departments. However, a downloadable smartphone application will lead many simultaneous visitors, who potentially will bump against each other. As such, there might be queues by limiting the devices, but much less usability concerns.

4.6. Conclusion

In this paper, through a field study in a real-world museum environment, we deployed a mixed-method evaluation methodology to investigate how AR enhances the communication of the architectural context of an isolated artifact. Our chosen artifact is a relief from the Nimrud palace in Iraq, exhibited at the Royal Museums of Art and History in Brussels. It is considered as an exceptional museum artifact due to the recent deliberate destruction of its original context.

We conclude the paper with a set of discussion points and design recommendations for future research or potential further development of AR applications that communicates heritage in museums. Our findings show several qualities of using AR in museums such as its positive effect on visitors' memorability of architectural qualities, particularly how they perceive and recall architectural features and spatial dimensions. Using AR in museums stimulates curiosity of visitors to explore more information. Several considerations about AR visualization are also highlighted, such as how levels of embellishment direct user's focus of attention. For uncertain heritage information, AR abstract visualization might be suited for communication, but aspects of transparency and choice of colors should be carefully considered. We outline several design recommendations to overcome current AR usability issues in museums about intuition, freedom of movement, and age-related differences.

Chapter 5:
Graethem Chapel

5

This chapter has been previously published as:

Eslam Nofal et al. (2018.c). "Communicating the Spatiotemporal Transformation of Architectural Heritage via an In-Situ Projection Mapping Installation", *Digital Applications in Archaeology and Cultural Heritage (DAACH)*, 11C (2018) e00083, DOI: https://doi.org/10.1016/j.daach.2018.e00083

Abstract

Understanding the spatial transformation of architectural heritage over time is crucial for documentation and conservation purposes, but also for communicating the salient architectural features of the buildings' evolution to the public at large. With the rapid evolution of physical computing technologies such as electronics, sensors and digital projections, we believe that the technique of projection mapping offers great potential in communicating heritage in-situ because its graphical depiction on the heritage itself can more directly relate to the real context in more experiential ways. Furthermore, digital projections can include various interactive functionalities that together with its architectural size provide an immersive experience that is dynamic and adaptable to the interests of the visitors. Consequently, this paper aims to investigate the deployment of an interactive projection mapping installation in-situ which can be steered by a tangible user interface (TUI). Through an in-the-wild study, we deployed a mixed-method evaluation to investigate how such an interactive projection mapping enhances the communication of the spatiotemporal transformation of a medieval chapel that occurred during the last 850 years. Our findings show how the in-situ projection positively affects visitors' understanding and memorability of the aesthetic features, and how its combination with a tangible interface enhances the communication of the spatial features of the chapel over time, and allows for more social interaction among them. The paper concludes with several discussion points and recommendations for applying interactive projection mapping and TUIs in the context of architectural heritage.

5.1. Introduction

Each heritage building typically possesses its own unique salient features that combined together forms its architectural and aesthetic value. Salient features of architectural heritage include those elements, details and decorations that define the functions and activities that the spaces host and determine the human perception and experience of space. The synthesis of spaces, volumes, materials, and constructive systems of architectural heritage results from various spatial and aesthetic transformation and modification processes over time [Brusaporci, 2015]. As such, architectural heritage also includes the significant and meaningful changes it underwent over time, such as in how a building and its various salient architectural features has been altered from one time phase to another.

Studying and communicating the spatiotemporal transformation of architectural heritage is crucial for documentation and conservation purposes [Doulamis et al, 2015; Fredheim and Khalaf, 2016], but is also gaining importance in the context of heritage democratization [Rodéhn, 2015]. ICOMOS charters stress the importance of heritage communication in order to heighten the public awareness and to enhance their understanding of cultural heritage [ICOMOS, 2008]. As such, heritage has to be presented in a way that it is physically accessible to the public, and the interpretation of the content should assist them in establishing meaningful connection to the heritage assets. Accordingly, our research is motivated out of the wish to make the spatiotemporal transformation of architectural heritage more accessible, relevant and experiential to a broader public.

During the last two decades, several emerging digital technologies already influenced the way of disseminating and communicating cultural heritage information [King and Stark, 2016]. These technologies typically vary in terms of modality, immersion and situatedness of the physical heritage environments. For instance, Augmented Reality (AR) technology allows for superimposed information or virtual objects as if they coexist in the real world [Azuma et al, 2001]. As such, AR promises heritage professionals the power to visualize and interact with monuments and heritage artifacts in more intuitive and direct, and thus also more appealing and exciting ways (e.g. [Mohammed-Amin, 2015; Nofal, 2013; Mourkoussis et al, 2002; Wojciechowski et al, 2004]. According to Milgram's Reality-Virtuality continuum (Figure 5-1), there exists two distinct techniques of AR to augment the user's view of the real world that could communicate heritage information within the confines of a physical building itself and in an architectural scale [Ridel et al, 2014]. So-called 'see-through AR' promises to facilitate learning and user engagement in heritage contexts by superimposing virtual objects on the real scene via portable (e.g. smartphones and tablets [Vlahakis et al, 2002]) or wearable devices (e.g. HoloLens [Pollalis et al, 2017]). In turn, 'spatial AR', sometimes known as 'projection mapping' or 'projection-based augmented reality' [Mine et al, 2012], augments the environment of the user with images or videos that are projected directly on the physical reality [Raskar et al, 1998]. In contrast to see-through AR, spatial AR does not require wearable displays or goggles, and is more apt in providing an experience that can be enjoyed by multiple people simultaneously.

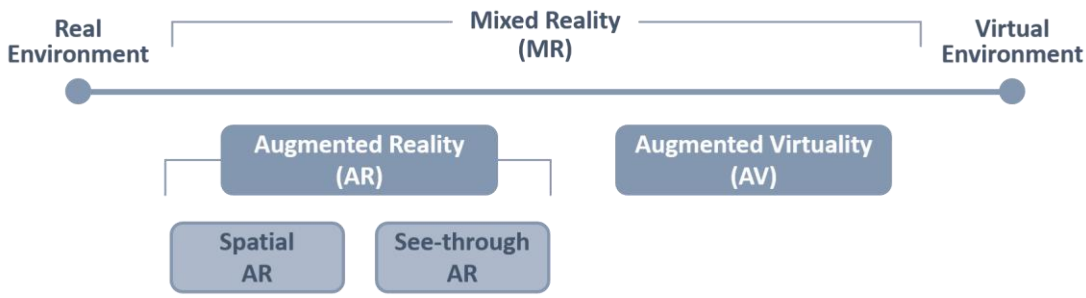


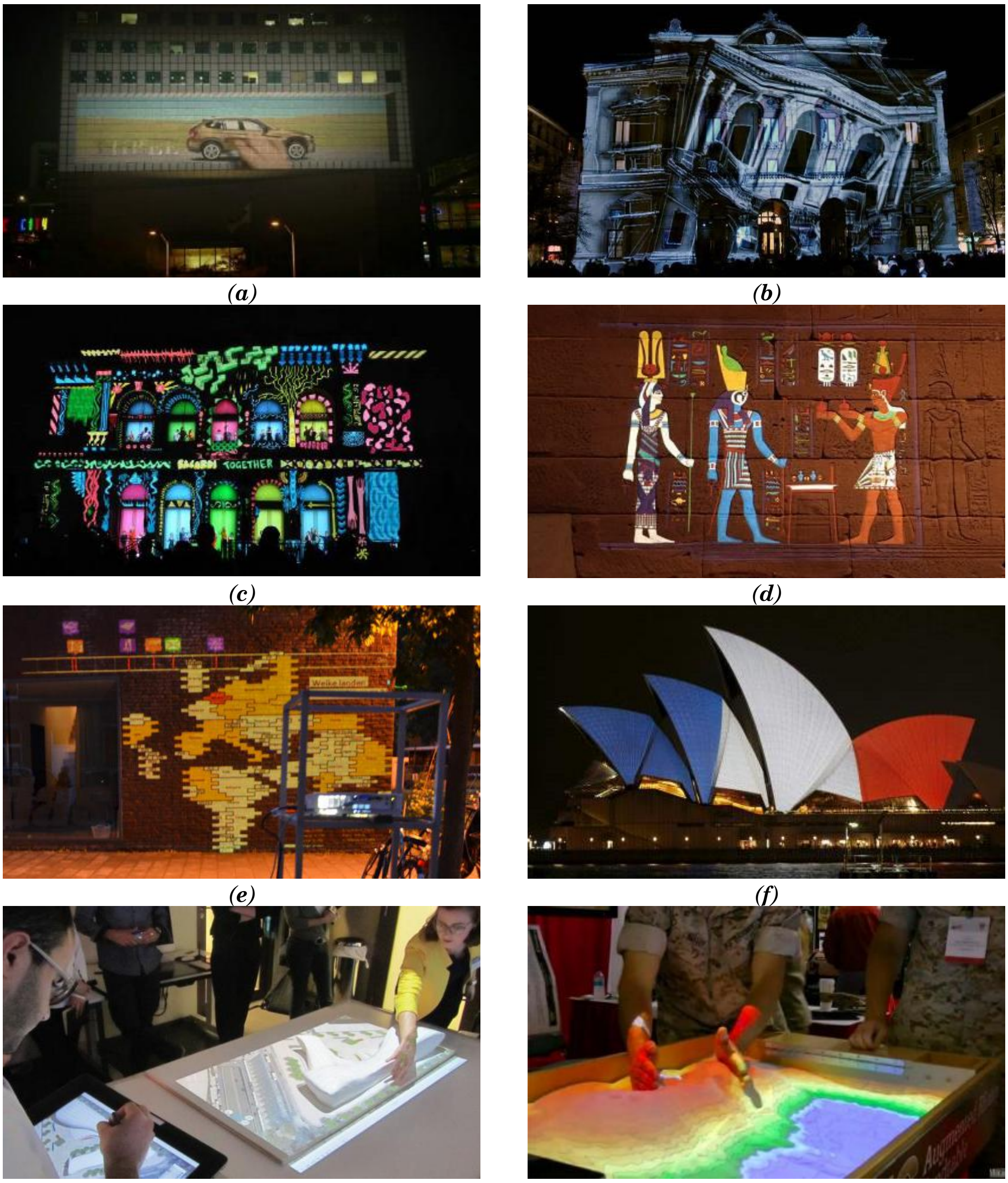
Figure 5-1: *AR techniques on Milgram's Reality-Virtuality continuum that apt in communicating heritage information in-situ [Authors after Milgram and Kishino, 1994; Ridel et al, 2014].*

As a communication medium, projection mapping possesses particular qualities that makes it relevant for conveying heritage information. Projection mapping is more situated as the graphical depiction of the information can be directly and physically related to the artifact on which the projection occurs [Rekimoto et al, 1998; Nofal et al, 2017.c]. The digital content communicates contextual information, such as the characteristics and cultural values of heritage [Kim, 2015]. Projection mapping is also effective in creating an outdoor performance to convey a message in a sociable and dynamic atmosphere [Kim, 2015].

Large-scale projection mapping vary from showing specific content from ex-situ projections that tend to relate to the building as a symbol to in-situ projections that tend to contextualize and highlight information within the space itself. Based on the contextual model of media architecture [Vande Moere and Wouters, 2012], we argue that the context of a projection mapping can be characterized by: a) the *environment*, including the physical environment, situated in a particular time, the people and their activities; b) the actual *content* that is communicated; and c) the *carrier* that supports the display medium, such as buildings, facades, ornaments. Projection mapping forms a unique medium in that, as the interpretation of its content typically depends on the interrelationship between the environment and the carrier. For instance, the projection of French flag colors (content) on the architecture of the Sydney Opera House (carrier) after the terrorist attacks in Paris (environment) in 2015 (Figure 5-2.f), was intended as expressing the Australian collective sense of sympathy to and solidarity with France. Figure 5-2.d shows the projection of real colored images (content) on an Egyptian temple wall (carrier) exhibited at the Metropolitan Museum of Art in New York (environment). This contextual relationship aimed to immerse museum visitors in an interactive real-world scale experience for better understanding the cultural heritage (i.e. real colors of the ancient Egyptian wall) [Waldek, 2016]. The wide spectrum of applying projection mapping allows for various purposes, such as:

- *Commercial* (Figure 5-2.a), such as the interactive advertising in public spaces, allowing the audience sufficient space to gather and watch an event.
- *Artistic* (Figure 5-2.b), such as showing synchronized animations on existing urban elements for arousing artistic emotion and for entertaining the spectators (fetedeslumieres.lyon.fr).
- *Cultural* (Figure 5-2.c and 5-2.d), such as the in-situ projection mapping for incorporating Cuban heritage onto Vienna's Kursalon building [Krautsack, 2011], and for projecting the real colors on a historic wall in a museum context.
- *Social* (Figure 5-2.e), such as mapping the socio-demographic facts (i.e. immigration map) for the surrounding unto the bricks of a house façade [Valkanova et al, 2015].
- *Political* (Figure 5-2.f), such as showing solidarity and sympathy by projecting the colors of a country's flag on the architecture of a landmark in another country for a specific event.
- *Educational* (Figure 5-2.g and 5-2.h), such as projecting a synchronized rendering on a white physical 3D model for supporting cooperative

architectural design of complex shapes [Calixte and Leclercq, 2017], or the interactive visualization of realistic terrains by moving the sand to manipulate a colored height map in real-time (military.com).



(a) (b) (c) (d) (e) (f) (g) (h)

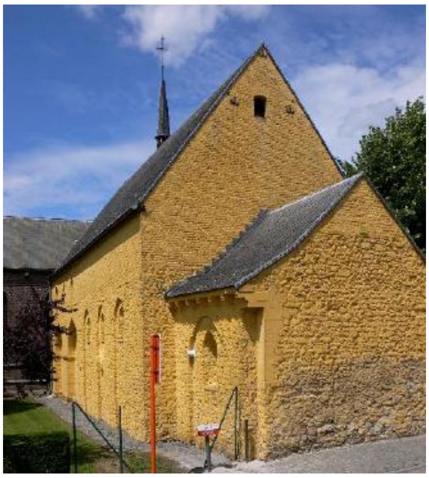
Figure 5-2: *Different purposes of interactive and in-situ projection mapping: (a) commercial: advertising of BMW onto two buildings of Sun Tec City in Singapore (coloribus.com), (b) artistic: showing synchronized animations on existing urban elements during the festival 'Fête des Lumières' in Lyon (fetedeslumieres.lyon.fr), (c) cultural: incorporating Cuban heritage onto Vienna's Kursalon building [Krautsack, 2011], (d) cultural: projecting the real colors on an Egyptian temple wall exhibited at the Metropolitan Museum of Art in New York (metmuseum.org), (e) social: revealing the origins of foreign inhabitants of a street by projecting the world map on a house façade as each brick corresponds to one person [Valkanova et al, 2015], (f) political: projecting the French flag colors on the architecture of Sydney Opera House after the terrorist attacks in Paris (abc.net.au), (g) projecting a synchronized rendering on a white physical 3D model during architectural design education [Calixte and Leclercq, 2017], and (h) educational: visualizing realistic terrains by moving the sand to manipulate a colored height map in real-time (military.com).*

Accordingly, this paper aims to communicate the spatiotemporal transformation of architectural heritage using interactive projection mapping to enable heritage visitors to appreciate heritage information in more experiential ways. In this study, we custom designed a tangible user interface (TUI) for interacting with the projection mapping. We deliberately chose a tangible interface as TUIs are believed to be more intuitive because they tend to communicate meaning through their physical affordances [Macaranas et al, 2012], such as by relating information into physical shapes and forms, or into particular material attributes (e.g. size, shape, texture, color, weight). TUIs possess unique qualities that enable communicating different forms of heritage information [Ciolfi et al, 2013], and tend to perform better in terms of memory and recall because they require more multimodal ways of human cognition to discover and decipher their meaning [Seo et al, 2015]. The explicit touch and manipulation affordances of TUIs have shown to attract more visitors towards more extensive forms of exploration during interactive exhibits [Ma et al, 2015]. Further, TUIs tend to require little experience or skills to be operated, and can function as simultaneous input and output mediums [Shaer and Hornecker, 2010]. When combined with digital information (i.e. projection mapping), the design of TUIs focuses on representing this information in a physical form, empowering users to interact with it [Wyeth, 2008].

Consequently, we hypothesize that an in-situ interactive projection mapping installation controlled by a TUI is potentially suitable to communicate the spatiotemporal transformation of architectural heritage. Through an in-the-wild study, we deployed a mixed-method evaluation to investigate how such a projection mapping enhances the communication of the spatiotemporal transformation of a medieval chapel during the last 850 years. We also examined the engagement of visitors during their interaction flow and how it affects their memorability and enhances their visiting experience of architectural heritage. In particular, the following research questions are explored: (a) how does in-situ interactive projection mapping influence the communication of spatiotemporal transformation of architectural heritage; and (b) how does the combination of projection mapping and TUI in an architectural heritage context affect user engagement?

5.2. Graethem Chapel

Because of its small size, rich building archaeological history, and touristic use, the Graethem chapel in the small town of Borgloon (Belgium, Province of Limburg) was chosen as a methodologically perfect case for complementary research with students [Coomans, 2011; Massart, 2014; Stevens, 2017]. The chapel is a medieval heritage building that is listed as a historical monument since 1936. It is no longer used for worship, but instead functions as a gallery for art exhibitions organized by the local cultural center. Tourists visit the chapel because it belonged to a Beguinage, i.e. a medieval urban Christian community of semi-religious women [Simons, 2003]. Beguinages are popular heritage since thirteen Flemish Beguinages were inscribed on the World Heritage list in 1998. However, the Graethem chapel's heritage value was not outstanding enough to become part of the World Heritage serial nomination. Today, indeed, the chapel is a simple rectangular nave of four bays, ending with a lower square sanctuary; nearly all the interior decoration and furniture have been lost (Figure 5-3).




(a) **(b)**

Figure 5-3: *The architecture of the Graethem chapel today; (a) exterior view from the south-east, and (b) interior view of the nave to the east [Photos THOC 2010].*

The main historical interest of this chapel is that Louis I, Count of Loon, was buried in the chapel in 1171 and his wife, Agnes of Metz, in 1175. For that reason, archaeological excavations were carried out and brought to light more tombs as well as foundation walls of parts of the chapel that disappeared in the course of time [Lux and Bussels, 1969]. The chapel's architectural evolution consists in eight main phases that have been accurately dated thanks to historical sources, archaeological contexts and tree ring dating of the timber roof structure [Coomans, 2011]. Digital reconstructions illustrate each phase [Massart, 2014]:

- *Ca. 1120* (Figure 5-4.1): the initial Romanesque stone chapel consist in a single nave of two bays and a small sanctuary with round apse lightened by small round arched windows. So the chapel looked like when Louis I and Agnes were buried there in 1171-75.
- *Ca. 1230-45* (Figure 5-4.2): an aisle is added at the northern flank of the nave, providing more space.
- *Second half of the 13th century* (Figure 5-4.3): the Beguines occupy the chapel from around 1250 and enlarge the nave by adding two aisled bays to the west; this extension is built with brick and has pointed arched windows and a higher volume.
- *Ca 1500* (Figure 5-4.4): the western part is redesigned by suppressing both aisles, opening a large late-Gothic traceried window in the west façade, and adding a square roof turret with a bell.
- *Ca 1658* (Figure 5-4.5): after religious wars and destructions, the Graethem chapel is restored, the vault of the sanctuary replaced by a ceiling, and the Romanesque part of the nave covered with a new roof that is as high as the roof of the Gothic part of the nave.
- *Ca 1720* (Figure 5-4.6): the main entrance is transferred from the northern to the western side of the chapel, on the main axis of the nave; large windows are pierced in the side walls of the nave.

- *19th century* (Figure 5-4.7): the Beguinage is suppressed by the French law of 1797 and the chapel is used by the new hospital built nearby. An annex is added against the southern side of the Romanesque part of the church and all the outer walls are coated in white. In 1870, the mausoleum of the Count and Countess of Loon is demolished and a wall with a sculpted decoration erected between the nave and the former sanctuary.
- *20th century* (Figure 5-4.8): after the construction of a new Gothic Revival chapel in 1911, the old chapel loses its function and is used as storage place by the hospital. Listed in 1936, the chapel is 'heritagized' and renovated in two campaigns, first in 1969, including archaeological excavations; second in 1993, when outer and inner coating hide most traces of patchwork stone and brick masonry resulting from the many transformations (Figure 5-3).

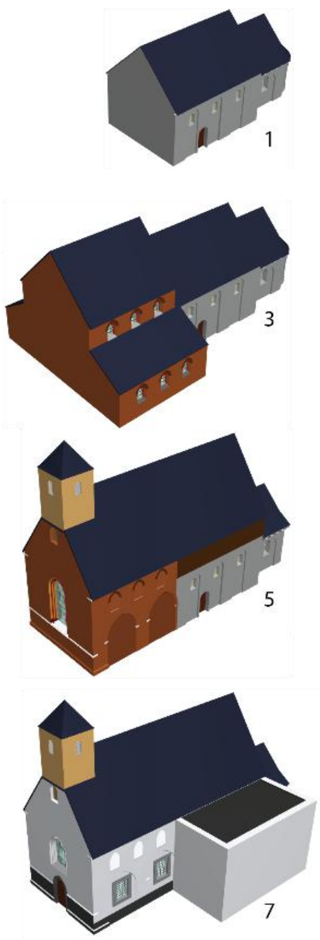


Figure 5-4: *3D models of the different building phases of Graethem chapel: (1) ca. 1120, (2) ca. 1230-45, (3) second half of the 13th century, (4) ca. 1500, (5) ca. 1658, (6) ca. 1720, (7) 19th century, (8) 20th century [Massart, 2014].*

5.3. Design and Development

5.3.1. Conceptual Design

As illustrated in Figure 5-5, the conceptual design of our interactive projection mapping installation consists of a freely rotatable digital projector that allows the interior view of the 3D digital models from the different building phases of the chapel to be superimposed on the existing walls of the chapel. A tangible user interface (TUI) is used to switch among the digital models that each represents a specific time period. In practice, visitors are invited to pick up one out of three physical models of a particular time period, touch it and place it on the designated platform. As illustrated in Figure 5-6, the projection content switches to show the particular interior simulation of the time period that corresponds to that physical model[1]. As a proof of concept and in order not to over-complicate the interface, we decided to limit the number of phases to three, instead of the eight mentioned in Section 2. In particular, we deliberately selected the initial phase, the current phase, and the phase from the 13th century as it witnessed the most significant major spatial transformation:

- *The 12th-century model (Ca. 1120)* is the initial state of the 12th century Romanesque chapel where Count Louis I was buried (Figure 5-4.1). Its inner space is smaller in length and height than today. The sanctuary is open to the nave through a round arch and ends in a semi-circular apse.
- *The 13th-century model (Ca. 1250)* dates back to the second half of the 13th century, when the Beguinage used the chapel and extended the nave (Figure 5-4.3), doubling its length with two aisled bays and a higher ceiling. In this phase the chapel reached its largest size.
- *The 20th-century model (1974)* is the current state of the chapel (Figure 5-4.8), which can potentially be used to show additional information in the existing space, such as a schematic, non-realistic representation of the age of all the construction elements inside and/or the visualization of the roof structure that is hidden above the wooden ceiling.

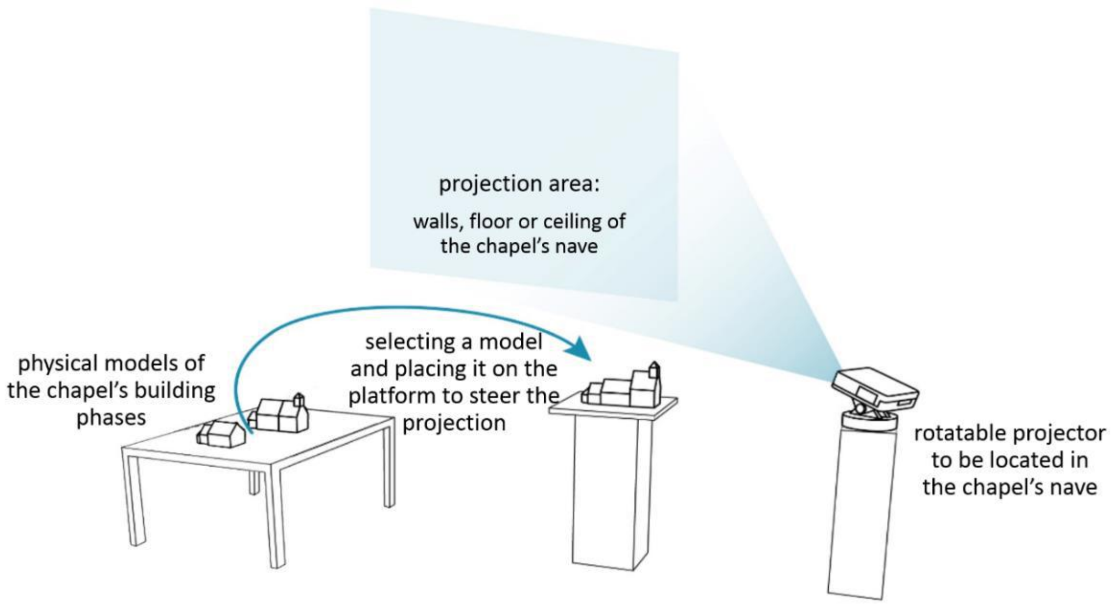


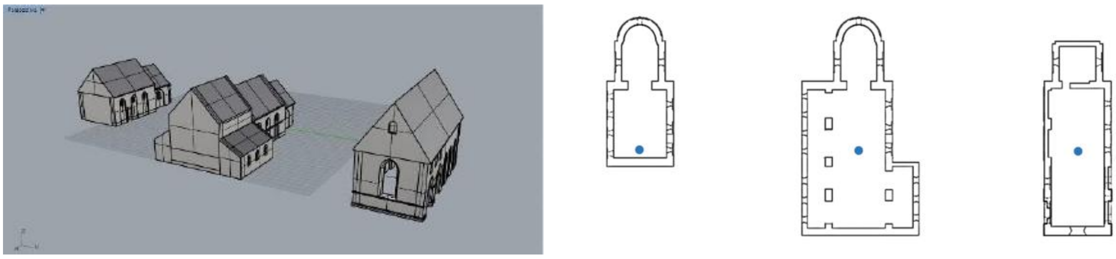
Figure 5-5: *Conceptual design of the installation: rotatable projector steered by a tangible user interface (physical models of the chapel's building phases that visitors pick up and place them on the designated platform).*

[1] A video showing the in-situ deployment of the installation is available on: https://vimeo.com/336829592

Figure 5-6: *Final design of the installation: a freely rotatable projector combined with a tangible user interface (physical models of the chapel's building phases that visitors pick up and place them on the designated platform to activate the projection).*

5.3.2. Digital Models

Based on the digital models of [Massart, 2014], we refined the exterior and interior of the three chosen building phases to add more details. Models were imported into Unity 3D software, and a virtual camera was added in each model in the same spot where the projector is positioned within the physical, in-situ space (Figure 5-7).



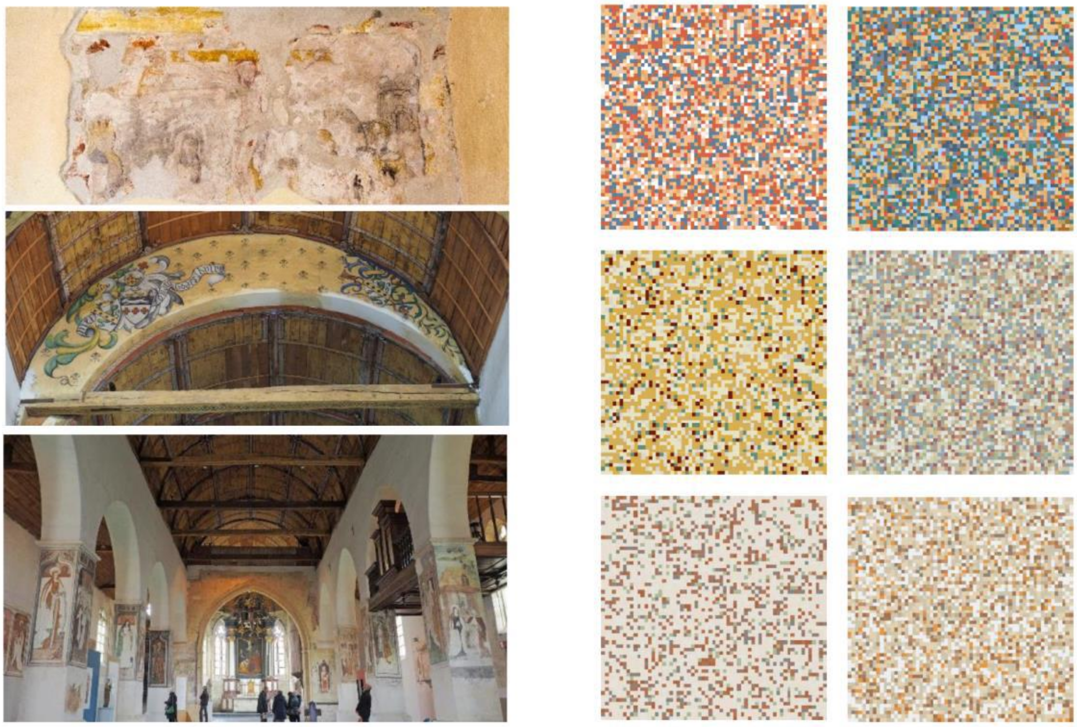
(a) ***(b)***

Figure 5-7: *The selected three building phases; (a) 3D digital models of the phases are imported into Unity 3D software, and (b) the blue dots indicate the location of the virtual camera in each model.*

The interior of the chapel still contains remains of mural paintings from the 14th to the 16th century [Bergmans, 1998]. These remains, however, are too scarce to authorize a reconstruction of the polychrome interior. Accordingly, we decided to visualize the paintings in an abstract representation, focusing more on the general colorful composition of the walls and colors, rather than on a detailed yet still hypothetical reconstruction. Several color schemes were created, relying on the ensemble of late medieval wall paintings of the Beguinage church of Sint-Truiden, a small town located 12 km west of the Graethem chapel, as shown in Figure 5-8.a [Coomans and Bergmans, 2008]. This church and its paintings are part of the World Heritage nomination of 1998. As indicated in Figure 5-8.b, we randomly assigned the color schemes to a matrix of squares in Adobe Illustrator, which were exported as

JPEG files. These images were used to develop 2D textures in Unity and finally attached to the according wall segments of the 13th-century model. In the 12th-century model, the ceiling and the western interior wall were rendered in a pure black texture, since in this phase the chapel was only about half its current size in length and significantly lower in height. The interior walls of the 20th-century model were simulated in a neutral white color, similar to its current physical state. Whilst, this digital model differs in showing the unique wood truss structure of the roof, which is currently physically hidden behind a flat wooden roof cladding.

In each digital model, we added several omnidirectional point light objects combined with a single external directional light, in order to obtain the shadows on the floor and a blue sky outside of the windows. In the 12th-century model, we adjusted the lighting parameters to visually darken the nave, yet in a very subtle way, as the space in the initial state used to be darker due to the low number and small size of the windows on either side of the nave.

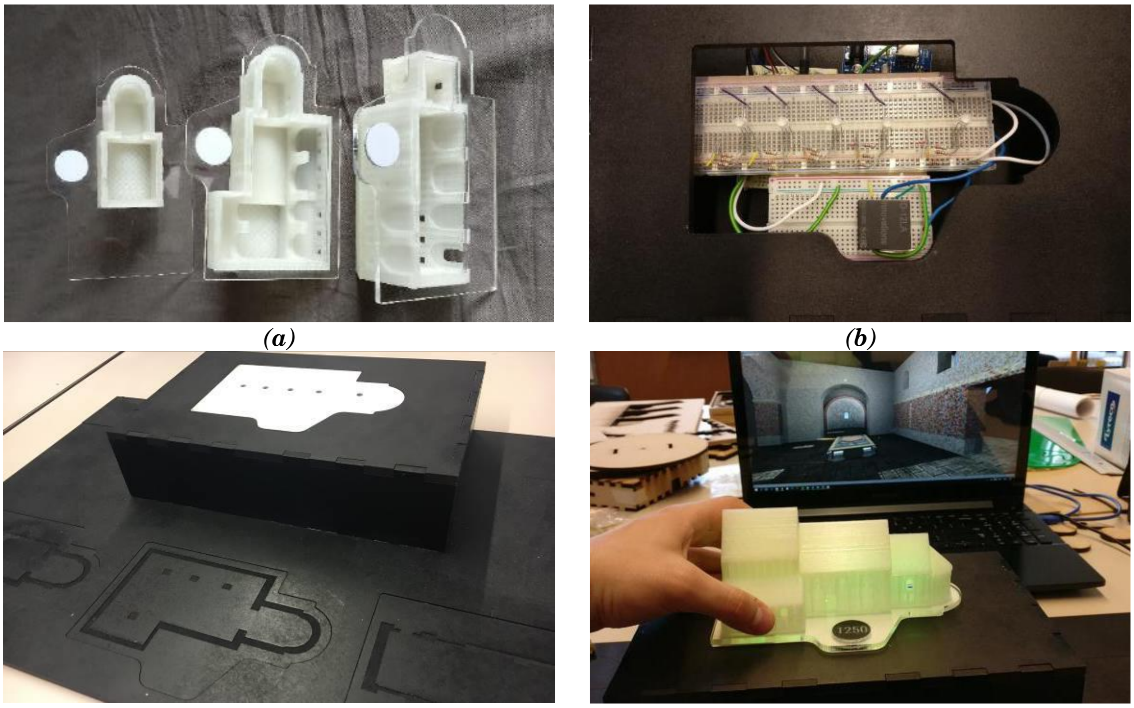


(a) *(b)*

Figure 5-8: *Visualizing the paintings of the chapel in an abstract representation; (a) details of the remaining mural paintings in the Graethem chapel (top) and contemporaneous wall paintings in the Beguinage church of Sint-Truiden (middle and bottom) [source: www.euroreizen.be]; (b) creating color schemes that used in reconstructing the walls and columns of the 13th-century model of the chapel.*

5.3.3. Tangible User Interface

We designed and prototyped a custom tangible user interface (TUI), which consists of a platform containing an RFID reader that was able to sense the RFID tags that were integrated within the physical models of the building phases. This reader connected to an Arduino Mega electronic board that sent a signal to a computer in order to switch to the corresponding digital model in the 3D Unity environment. The shape of each physical model corresponds to the digital models, which were 3D printed in a semi-translucent white polymer to allow LED light to be emitted through them (Figure 5-9.d). In addition, each model was purposefully hollowed out to allow users to examine and touch both its inside and outside characteristics (Figure 5-9.a). As a visual feedback, a row of LEDs was integrated in the platform to light up the physical model when the RFID reader detected one of the tags (Figure 5-9.b). The contour shape of the floor plan of each building phase was engraved on the platform to maintain their chronological order, as a subtle relief was cut out along the circumference of the base plates' places to provide for a perfect physical alignment for the models when being manipulated by users (Figure 5-9.c).



(a) ***(b)*** ***(c)*** ***(d)***

Figure 5-9: *Design decisions for the tangible user interface; (a) 3D printing the models by hollowing them out, then placing them on plastic base plates including the RFID tags, (b) integrating a RFID reader and a row of LEDs inside the platform, aligned to the base plates of the models, (c) engraving the floorplan on the platform and cutting out a subtle relief to be physically aligned with the plastic base plate, and (d) testing the interface at the lab with the second model, where the LEDs are emitting a green light through the physical model and the screen displays the digital model of the building phase.*

5.4. Evaluation Methodology

In order to determine how our installation performed in communicating the spatiotemporal transformation of the Graethem chapel, we followed a mixed-methods, in-the-wild evaluation study that commenced with analyzing the performance of a low-fidelity prototype, followed by a pilot study at the chapel itself. Eventually, the final in-situ study was carried out with 28 visitors.

5.4.1. Evaluation Methods

Casual chapel visitors were invited to interact with our installation by selecting a physical model and placing it on the platform to steer the projection mapping of the corresponding building phase on walls, ceiling and floor. Their interaction was observed, as they were allowed to freely select any of the physical models and rotate the projector. Thereafter, we invited them to participate in a semi-structured interview and asked them to sketch a cross section of the chapel, and fill in a standardized user experience questionnaire.

5.4.1.1. Observation

All the interactions were video-recorded, observed and manually analyzed in an Excel spreadsheet. The level of user engagement was derived by the duration of their interaction, their focus of attention while interacting and their social interactions with other person(s) nearby. Furthermore, from the video recordings, we graphically labelled the time of interaction of each building phase for each participant. We also observed whether visitors mapped the physical models with what they perceived via the projection content, or whether they were able to make meaningful comparisons among the building phases.

5.4.1.2. Semi-structured interview

After interacting with the installation, participants were invited to a semi-structured interview that was audio-taped. The questions focused on revealing the comprehension of the spatial transformation of the chapel over time by asking them to describe the differences between the building phases in terms of space, dimensions, colors and lighting. More qualitative questions queried the participants' impression of using such technology in heritage environments (e.g. what they liked, what they disliked, and why). Participants were handed a simplified cross section of the current building phase through the eastern side of the nave, and invited to sketch a cross section of the 13th-century building phase based on what they remembered from the projections and the physical model. All answers from the interviews were then manually analyzed using an Excel spreadsheet by dissecting how they interpreted the spatiotemporal transformation, such as how they described the chapel in each phase and its salient architectural features. In addition, participants' quotes from the interview were manually transcribed.

5.4.1.3. User experience questionnaire (UEQ)

Subsequently to the interview, participants were asked to fill in a standardized user experience questionnaire (ueq-online.org). The UEQ has proven to be an efficient assessment of the user experience of an interaction design [Laugwitz et al, 2008], as it is a statistically valid method that allows participants to express their subjective feelings, impressions or attitudes. The questionnaire consists of six different scales with 26 items in total, covering a relatively comprehensive impression of user experience, including: 1) *attractiveness*, or the general impression of users, such as whether users liked or disliked it; 2) *efficiency*, such as whether users were able to use the installation efficiently, and whether its user interface looked organized; 3) *perspicuity*, or whether the installation was easy to understand in how it can be used; 4) *dependability*, or whether the user felt in control of the interaction in terms of security and predictability; 5) *stimulation*: whether they found it interesting and exciting to use; and finally, 6) *novelty*, in that the installation was considered to be innovative and creative.

5.4.2. Study Setup

The whole evaluation study commenced with a low-fidelity test session at our research lab with only a few number of participants, followed by a one-day in-situ pilot study at the chapel itself. Thereafter, we carried out the final in-situ study during approximately one week. All participants signed an informed consent form to confirm that they voluntarily participated and that the results of this research can be used only for scientific purposes.

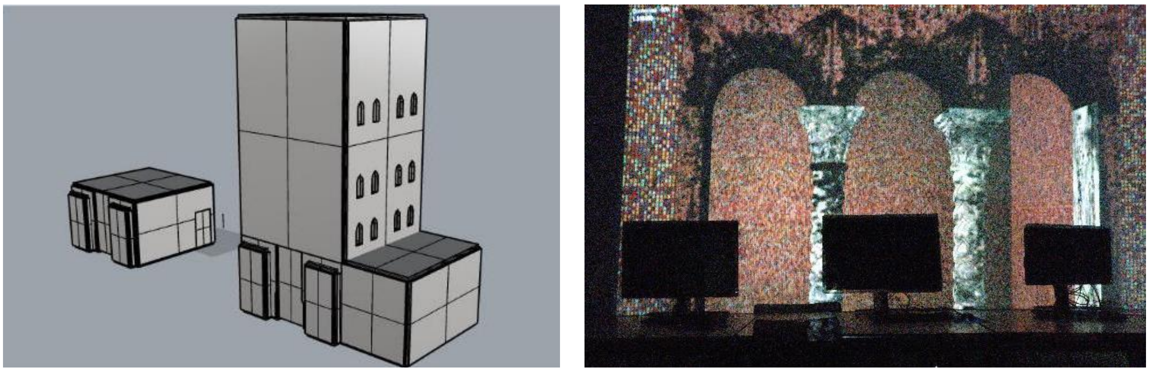
5.4.2.1. Lab study

A low-fidelity prototype was designed and implemented at the lab, consisting of a smaller projector that demonstrated the conceptual approach (Figure 5-10). The installation consisted of a swing-style suspension to maintain the balance of the projector and to avoid toppling it over when released, a ball bearing system to support the weight of the projector, and a rotary encoder to be able to measure the precise tilting angles.

(a) *(b)*

Figure 5-10: *Low-fidelity prototype; (a) a swing-style suspension to maintain the balance of the projector, and (b) a ball bearing system to support the weight of the projector, with a rotary encoder in the center.*

An imaginary scenario of the room (i.e. lab) with a higher ceiling and a connection to another space through archways was modeled (Figure 5-11.a) to be tested through projection in the lab (Figure 5-11.b). The subsequent analysis of the lab study led to several technical modifications, such as the need to continuously calibrate the camera orientation, and to tackle the issue of projector's asymmetrical field of view. Ergonomic alterations were also made to make sure the installation is fixed during the experiment and to attach the projector cables inside the installation itself.

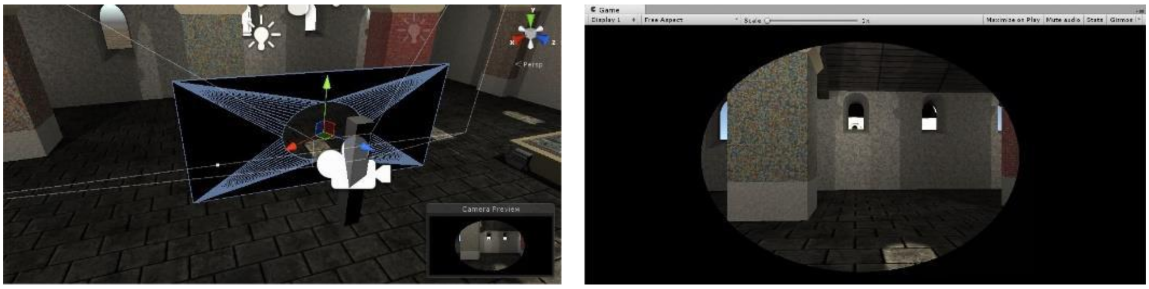


(a) *(b)*

Figure 5-11: *Imaginary scenario for the lab study; (a) modelling a higher ceiling of the room with a connection to another space, and (b) projecting the fictional space through archways on the lab's wall, i.e. behind the computers.*

5.4.2.2. Pilot study

The one-day pilot study in the main nave of the chapel aimed to reveal easily avoidable usability issues in an ecologically valid context, such as whether visitors could intuitively understand how to interact with the installation. Participants were introduced by a brief explanation about the historical value of the chapel and the purpose of the installation. Participants included members of the municipality, culture service, and architectural design students. Subsequently, we had an open discussion with them that provided us several insights to modify the installation. Based on the results, several modifications were implemented, such as: 1) including an elliptical projection frame (Figure 5-12) to be more 'natural' instead of the rigid rectangular frame that could be slightly unaligned with the physical wall because of the accuracy level of the motion sensor; and 2) placing one of the physical models on the platform instead of starting off with a black screen to provoke visitors' curiosity to interact with the installation.



(a) *(b)*

Figure 5-12: *Elliptical projection frame; (a) two dimensional oculus-object added to the virtual camera, and (b) a preview of the camera.*

5.4.2.3. Final study

The final study was deployed at different times to maintain ecological validity (i.e. weekdays and weekend) over a total period of one week. During this period, the chapel was freely accessible to the public. Via social media, posters in the city center, physical and electronic newsletters, the inhabitants of Borgloon and the surrounding villages, as well as other potentially interested people were invited to visit the chapel and interact with the installation.

5.5. Results

The final study involved 14 participants who took part individually (N=3) or in groups (N=11), so the total number visitors is 28. They form heterogeneous user groups of visitors, as they varied in gender (i.e. 14 males and 14 females), age range (i.e. 2 teenagers, 13 adults, and 13 elderly), and the purpose of their visit (i.e. 2 family visits, 1 passersby, and 11 tourists). We categorize our results into two sections: (a) whether and how interactive projection mapping facilitates the communication of the spatiotemporal transformation of the chapel; and (b) how the combination of projection mapping with a TUI increases the engagement of chapel visitors.

5.5.1. Comprehension of the Spatiotemporal Transformation

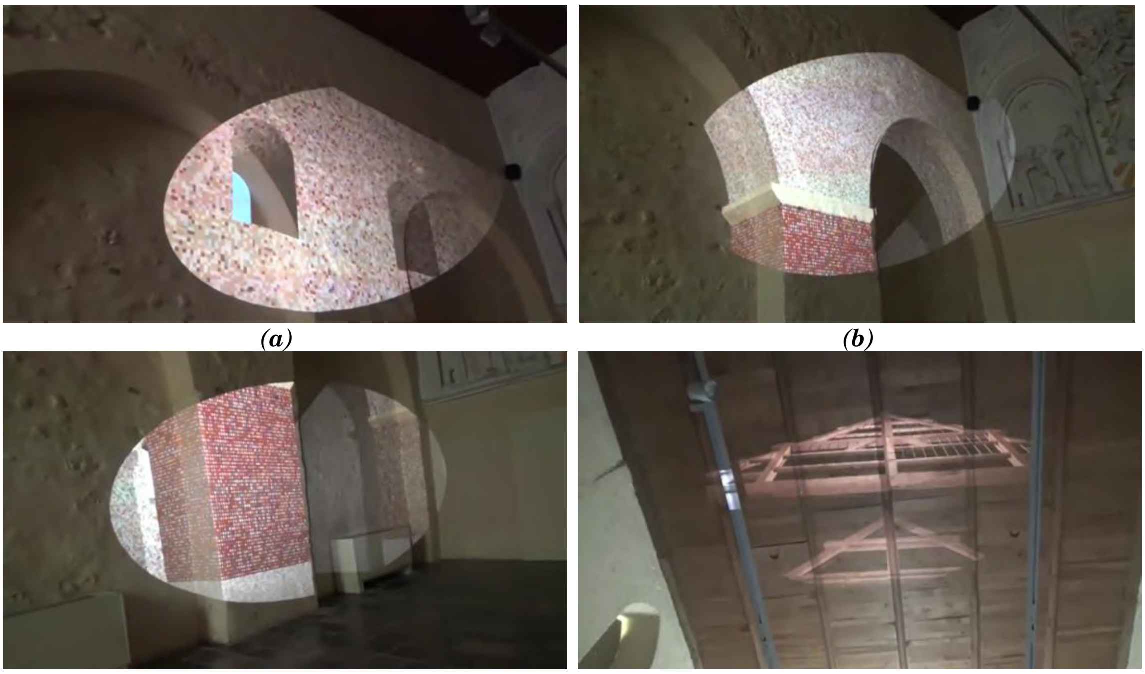
The results reveal that manipulating the physical models and rotating the projector at the same time allowed visitors to acquire spatial information about the chapel over time. They were able to report on the spatiotemporal transformation in a chronological order from the 12th-century model to the 20th-century model, recalling several architectural and aesthetic features from each of the building phases.

For the 12th-century model, visitors noticed four salient features: the lower and shorter space (N=14), the connection with choir and apse (N=8), the door in the southern wall (N=4), and the windows in the northern wall (N=2). Through projections, all participants (N=14) noticed the difference of height and length of the 12th-century model (Figure 5-13.a). Additionally, most of them (N=10) mapped this difference to the physical model, or to the existing visual and material clues (i.e. texture-difference of the actual wall of the chapel), indicating that the chapel was previously smaller. Some participants (N=4) linked this difference to the imbedded copper rivets in the floor to the original western façade.

For the 13th-century model, visitors noticed four salient features: the extension of archways and aisles (N=13), the colorful wall paintings (N=11), the higher ceiling in the west side (N=10), and the small windows on the outer walls of the aisles (N=7). The communication of these salient features resulted from both mediums the projection and the TUI. Some participants (N=6) noticed the archways and aisles first through the projection, and then observed the corresponding physical model to confirm their interpretation. While some other participants (N=5) noticed the columns and the aisles on the physical model first, and after that they were keen to see these changes via the projection (Figure 5-13.b). The others (N=3) already knew about the aisles due to their prior knowledge about the history of the chapel. Concerning the colors and textures of the chapel, most participants (N=11) recognized that the interior of the 13th-century model was more colorful than the current state of the chapel. When we explained to them the rationale of the polychromic texture, many of them (N=7) recalled that the columns in the projection were more prominently colored than the other parts of the interior (Figure 5-13.c).

The interpretation of the abstracted polychromatic textures on the walls of the 13th-century model was not intuitively understandable for the participants. Some of them (N=6) asked whether this 'mosaic' was actually present in the past, while few participants (N=2) assumed this was just an artistic representation. Other participants (N=6) did not know what it was supposed to represent. After explaining to them the purpose of using such polychromic texture in our design, they understood the significance and implication of these textures.

For the 20th-century model, less architectural salient features were communicated in comparison to the other two phases. That might well be the result of small changes with the current reality that are difficult to be found and remembered. Three salient features were noticed by the visitors: the higher ceiling in the east side of the nave (N=8), the hidden wood truss structure of the roof (N=6), and the disappearance of the apse (N=2) compared to the previous phase. For instance, when participants (N=6) directed the projector towards the ceiling, they discovered the hidden wood truss structure of the roof (Figure 5-13.d).



(a) ***(b)*** ***(c)*** ***(d)***

Figure 5-13: *Some salient features that participants recalled from their interaction; (a) the original Romanesque windows in the northern façade, indicating the difference in the chapel's height, (b) the archways to the northern aisles in the 13th-century model, (c) the colorful columns in the 13th-century model, and (d) the hidden wood truss structure of the roof of the 20th-century model.*

The interpretation of the abstracted polychromatic textures on the walls via random patterns was not as straightforward as expected. Only few participants (N=3) assumed it was just an artistic representation, while others asked what it was supposed to represent (N=5) or whether this mosaic actually existed in the past (N=6).

Furthermore, we reveal that the sketching of the cross section of the 13th-century model (Figure 5-14.a) allowed participants to report on several salient features. For instance, 13 participants (N=14) drew the aisle on the left (northern side), 13 participants drew the arch connecting the nave with the choir (Figure 5-14.b), 7 participants drew a line to indicate the lower ceiling height (Figure 5-14.c), and only 2 participants sketched the windows of the apse (Figure 5-14.d).

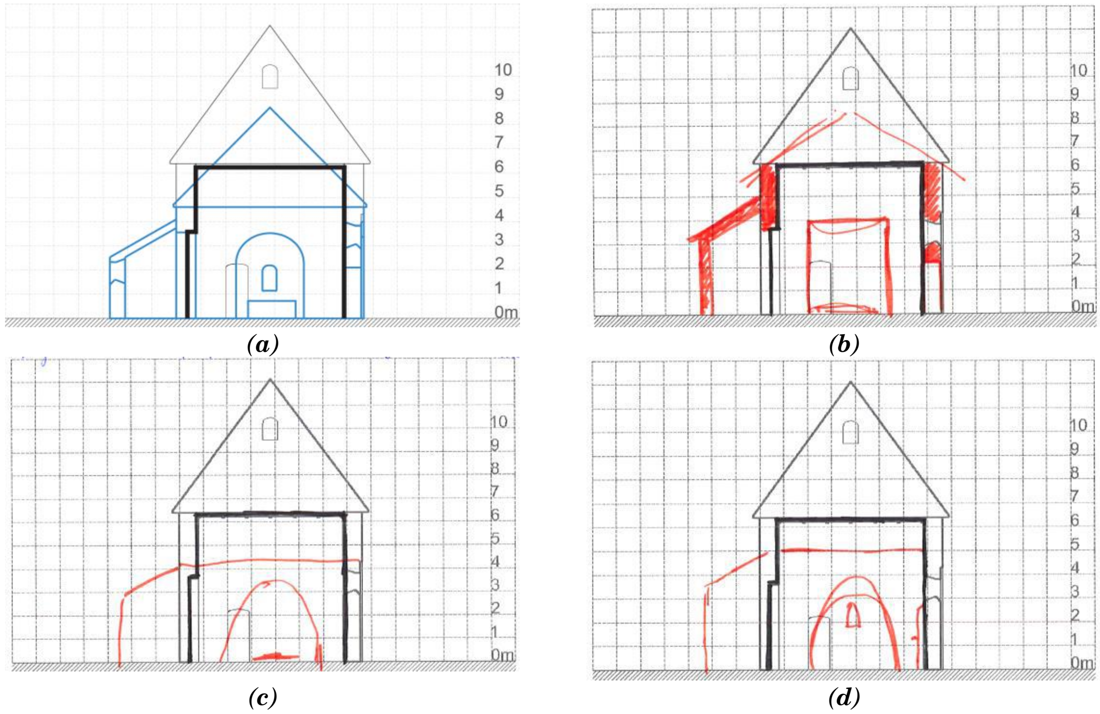


Figure 5-14: *Sketching a cross section of the 13th-century model on a grid paper; (a) the correct section (in blue) compiled with a cross section of the current state (in black), (b) sample of sketching the northern aisles and the opening to connect the nave to the choir (participant 6), (c) sample of sketching the lower ceiling height (participant 14), and (d) sample of sketching the window of the apse (participant 11).*

We combined the results from the interviews and the sketches in Table 5-1, showing how participants recalled the salient features and differences between the three building phases of the chapel. In general, we observed that our installation performed better in communicating the spatial features (i.e. lower and shorter space in the 12th-century model, extension of archways and aisles in the 13th-century model, and the higher ceiling in the east side of the nave in the 20th-century model) and aesthetic features (i.e. the colorful wall paintings in the 13th-century model), more than the functional features (i.e. existence of doors or windows in the three models).

Table 5-1: *Recalling the salient features from the three building phases of the chapel.*

Building phase	Salient feature	Number and percentage of participants who recalled this feature [1]	
12^{th}-century model *(Ca. 1120)*	Lower and shorter space	14	*100 %*
	Connection with choir and apse	8	*57 %*
	Door in southern wall	4	*29 %*
	Windows in the northern wall	2	*14 %*
13^{th}-century model *(Ca. 1250)*	Extension of archways and aisles	13	*93 %*
	Colorful wall paintings	11	*79 %*
	Higher ceiling in the west side	10	*71 %*
	Small windows on the outer walls of the aisles	7	*50 %*
20^{th}-century model *(1974)*	Higher ceiling in the east side of the nave	8	*57 %*
	Hidden wood truss structure of the roof	6	*43 %*
	Disappearance of the apse	2	*14 %*

[1] Total number of participants (N=14).

5.5.2. User Engagement

In this section, we report on participants' forms of engagement and appreciation, and their answers of the user experience questionnaire.

5.5.2.1. Level of engagement

In general, individual participants spent less time interacting (9:40 minutes, avg.) in comparison to groups of participants (13:10 minutes, avg.), as the common discussion between group members encouraged them to direct the attention to more and more diverse topics. For instance, group participants tended to divide their interaction roles, such as by allowing one of them control the projector and the other(s) handle the physical models, and then they switched the roles.

Figure 5-15 illustrates the duration and the order of interacting with the three building phases. Most participants (N=12) started their engagement by placing the 12th-century model, and then continued in a chronological order, as illustrated in Figure 5-15. Other participants (N=2) started with the 13th-century model as it was already placed on the platform prior their interaction. We noticed also that most participants (N=10) had a complete cycle of the three phases only once, while others (N=4) went back and forth among the building phases and started to make comparisons for feature by feature when noticed. The demographic information of those participants who switched back and forth among the building phases, shows a bias towards technological proficiency as they were mostly students, architects and teachers.

The chronological analysis, illustrated in Figure 5-15, shows that participants spent much more time interacting with the 13th-century model (5:50 minuets, avg.) compared to the 12th-century model (3:49 minutes, avg.). This might be due to the higher number of details in that building phase, which is relatively divergent from the current state of the chapel. In contrary, participants spent the least amount of time interacting with the 20th-century model (2:46 minutes, avg.), which was expected as there was almost no differences with the current state to notice.

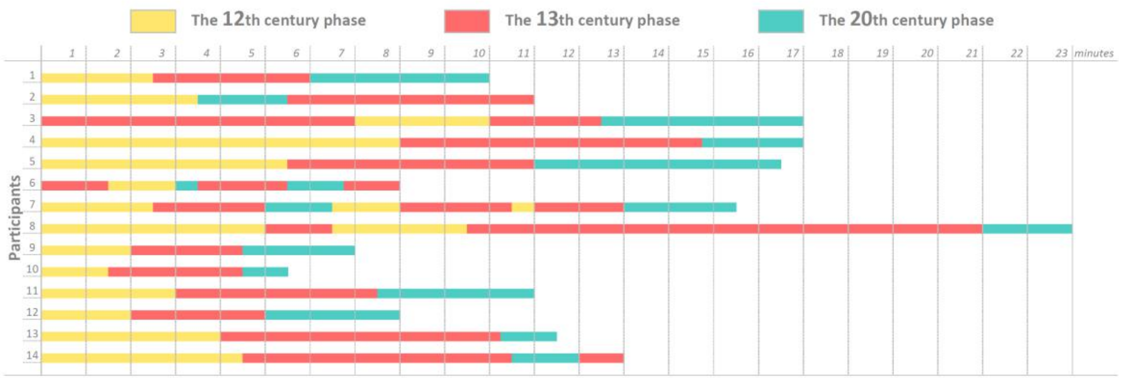


Figure 5-15: *Chronological analysis of participants' interaction.*

Our observation showed the advantage of combining two different interaction modalities. Most participants (11, N=14) did not use the physical models only to steer the projection, but they also examined them from outside and inside. As the projections provided some clues about the spatial features, they still wanted to double-check their understanding by looking carefully to the physical models. Examples of these features are (a) the lower ceiling in the 12th-century model compared to the actual state of the chapel's height; and (b) the extension of the archways with the side aisles in the 13th-century model which they do not exist anymore. In an opposite way, some participants directed the projector towards other salient features they noticed from the physical models, such as the location of the old side entrance in the 12th- and 13th-century models.

5.5.2.2. User experience questionnaire (UEQ)

All UEQ items were scaled from -3 (representing the most negative answer) to +3 (representing the most positive answer, when 0 is a neutral answer). The results of the UEQ, illustrated in Figure 5-16, demonstrate the general tendencies in how the installation performed. The Alpha-Coefficient value showed a high consistency for the items of attractiveness, perspicuity, efficiency, stimulation, and novelty scales. In contrast, the value was lower than 0.7 for the dependability scale, probably meaning that these questions (i.e. in the Dutch version of the UEQ) were possibly misinterpreted in a direction that does not reflect the intention of the participants within the context of UEQ [Rauschenberger et al, 2013].

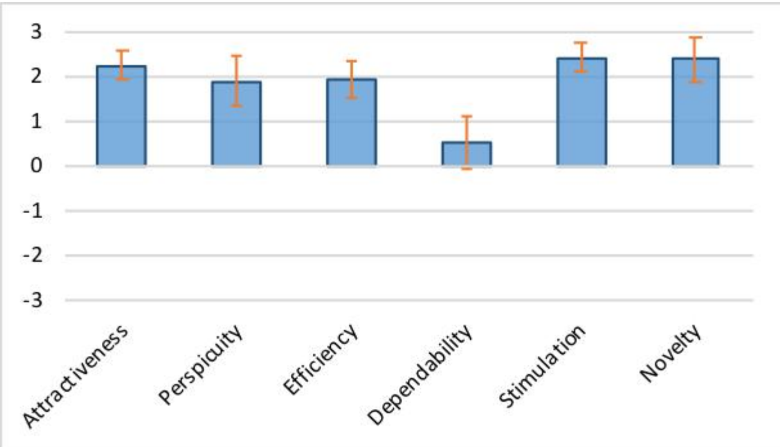


Figure 5-16: *Results of the six scales of the UEQ (the error bars represent the 95% confidence intervals of the scale mean).*

5.6. Discussion

In this section, we discuss the implications of the results with relevance to future research or potential further developments of interactive projection mapping in an architectural heritage context. We explain the qualities of interactive projection mapping and discuss the role of TUI in communicating salient features of architectural heritage. We outline several design recommendations to overcome current usability issues about physical affordance, robustness and the entertaining role of design.

5.6.1. Role of In-Situ Projection Mapping

The qualities of an in-situ projection mapping on a scale 1:1 facilitate the communication of particular aesthetic features of architectural heritage. The ability of controlling and rotating the projection allows for an interactive experience for heritage visitors.

Visitors were able to compare the projection in a real scale with the actual situation, as the graphical depiction of the projected information physically and contextually related to the walls and ceiling of the chapel. They were be able accordingly to report on its aesthetic features such as the colorful wall painting in the 13th-century model. Our findings reveal that the projection enabled participants to focus more on the atmosphere of the chapel, such as materials, colors and lightings for the different building phases. Atmosphere in architectural spaces refer to an immediate form of physical perception, and is recognized mainly through emotions. [Zumthor, 2006]. Participants tended to describe the chapel linked to their emotional perception and aesthetic appreciation for each building phase. For instance, instead of describing the 12th-century phase as a smaller nave with a lower ceiling and smaller windows, they described it as *"the first phase was a bit darker, but also cozier and more intimate"* (participant 1). Further, instead of describing the 13th-century phase as a larger space connected to the aisles, having a more colorful paintings, they described it as *"the second phase was more spacious and vibrant"* (participant 3).

Moreover, we found that visualizing the uncertainty of the polychromatic textures of the chapel's walls was challenging in a digital 3D model. Similar to virtual and augmented reality, people cannot handle well abstract information via projection mapping that moves away from realistic rendering. In projection mapping, rendering must be semi-realistic in order not to break the immersion, such as blurring real images of actual murals, or considerably reducing their resolution. Thus, textures would still show somewhat recognizable shapes and figures, instead of being completely random.

Furthermore, the power of rotating the projector in multiple directions (Figure 5-17.a) allowed for an interactive experience for visitors. Unlike the passive experience of omnidirectional projectors that reveal the information all at once, the partial boundary between digital and physical (i.e. elliptical projection frame) encouraged visitors to easily compare the existing situation of the chapel with the previous building phases. The freely rotatable projector stimulated visitors to orient themselves vertically and horizontally, even if motor actions from neck and face were required [Hands and Stepp, 2016]. They were able to explore the hidden details of the building, which were not easily accessible to them, such as directing the projector toward the ceiling and visualizing the hidden wood truss structure of the roof in the 20th-century model (Figure 5-13.d). The ability of controlling the projector made the visitors' experience more natural as their location and direction are physically linked to the existing space, they do not need to remember a mouse position like in computer screens. Controlling the projector enabled them also to steer it towards where other visitors were looking at, allowing for more collaborative experience.

Accordingly, we consider in-situ projection mapping as an effective medium to communicate the aesthetic features of architectural heritage. Yet, uncertainty of these aesthetic features should be visualized in semi-realistic representations in order not to break the immersion. We believe that the intrinsic qualities of projection mapping in communicating the spatiotemporal transformation of heritage result from the ability of controlling and rotating the projector in-situ. Such interactivity allows heritage visitors to compare the different building phases, explore the hidden details of the building, and collaboratively experience the space.

(a) *(b)*

Figure 5-17: *Chapel visitors interacting with the installation; (a) a group of participants dedicates the role of rotating the projector to one of them while the rest focuses on the projections and/or the physical models, and (b) a group of participants where one member is controlling the projector while the rest is gesturing towards the projections and explaining their interpretations.*

As a potential challenge of projection mapping, building façades or internal walls are required to be exposed to a relatively high light intensity [Sueishi et al, 2016]. Whilst, light energy acts as a catalyst for the chemical reactions that break down materials used in heritage artworks, as it is well known that flash lights are not permitted in most museums and heritage buildings. In our study, due to the loss of interior decoration of the chapel, its walls are lightly colored. However, in other heritage buildings, the high intensity of projections might gradually damage the historical materials. Consequently, when applying projection mapping in a heritage building, the international accepted standards of light exposure to heritage should be well considered.

5.6.2. Role of the TUI

The TUI plays a complementary role in communicating the spatial configuration of architectural heritage. The interplay between the two modalities of projection and TUI strengthen each other and enhances the communication of the spatiotemporal transformation of architectural heritage.

Interacting with the physical models of the TUI enabled visitors to comprehend the spatial configuration of architectural heritage [Bafna, 2003]. They focused more on the arrangement and the relationships of spaces to understand the spatial transformation of the chapel over time. Although many participants did not look at the physical models from inside, they acknowledged the value of touching and manipulating the physical models with their hands, and visually investigating the models from above to understand the spatial configuration of the chapel in each building phase. Examples of these spatial configurations are the extension of archways and aisles in the 13th-century model, and the connection with choir and apse in the 12th-century model.

Furthermore, our observation showed that the interplay between the TUI and the projection, or the blend of communicating spatial and aesthetic features of the chapel led to an "imaginative perception" [Scruton, 2013], which is how visitors might perceive the details of architectural heritage according to their imagination. Since the physical models were fabricated as white, monotonous sculpture, the qualities of colors and materials (i.e. aesthetic) were conveyed only through the projection. While manipulating with the physical models and having an overview of the building from above convey a graphical representation of the interrelated spaces (i.e. spatial). Such perception might benefit the communication of the spatiotemporal transformation of heritage for making interpretative choices in parsing ambiguous or multiform aspects of architectural heritage [Fisher, 2015], such as whether visitors see a sequence of columns as grouped one way or another, or they see pilasters as ornamental or structural. Moreover, combining the TUI with projection stimulates the visitors to explore more and to double-check their comprehension of architectural heritage, as when they saw a specific salient feature through the projection they tended to examine the physical model to confirm their understanding or vice versa.

Accordingly, we suggest that not only one interaction modality is ideal for all the required tasks in heritage communication. We recommend projection mapping to communicate the atmospheric experience of architectural heritage including the aesthetic features, and TUIs as a complementary modality to communicate the spatial configuration of buildings. While, combing both modalities in one interaction design might well benefit the communication of the spatiotemporal transformation of architectural heritage.

5.6.3. Interactive Projection Mapping Supports Social Interaction

The interactive projection mapping controlled be a TUI encourages the social interaction among heritage visitors.

The setup of the installation allowed for the projections to be experienced by multiple visitors, and the physical models can be shared and given to each other. This setup implicitly encouraged participants to take on different roles of interaction. For instance, a leader who was the responsible of rotating the projector by the two handles, a follower who was just following the information through projections, an explorer who was responsible of placing the physical models on the platform, or an interpreter who was able to map the information from projections to the physical models or to the existing visual and material clues (Figure 5-17.b). Most of the time, visitors switched the roles among themselves. Accordingly, they had almost a continuous discussion over the spatiotemporal transformation of the chapel and how each element was different from a phase to another as articulated in the results section. These discussions among the groups encouraged them to explore the installation more and to spend longer time of interaction, leading to more social interaction and higher levels of appreciation.

Consequently, for encouraging social interaction, we recommend designing an experience that can be shared and physically explored by multiple visitors. For instance, at least two visitors can be physically engaged by combining two communication mediums. This combination might stimulate other visitors to approach the installation, rather than socializing only with peers.

5.6.4. Usability

In-situ interactive installations require that each modality possesses its own affordances, which should be subtle in order not to overwhelm and distract. From the observations, we found that the two handles of the projector triggered participants to hold them and to rotate the projector horizontally and vertically (Figure 5-17.a). Participants were also encouraged to pick up and place the physical models on the empty white space on the designated platform. An immediate visual feedback was given to them when RFID reader detects one of the tags (Figure 5-9.d). Despite of the aforementioned considerations, we realized that the installation was not so intuitively understandable to most of visitors, which encouraged us to increase the affordance after the pilot study by placing one of the physical models on the platform as an interaction trigger. Accordingly, we recommend when technology is too novel to public as they do not know how to start, the installation should be self-explanatory to provoke their curiosity to interact with. For instance, a projection in real scale garbs the attention of visitors, particularly when it includes a kind of animation or tells a narrative via a voice, while a TUI in a heritage environment encourages visitors to grasp the physical models, taking into consideration not only the graphical characteristics but also aspects such as embodiment, physical abstraction, and materiality (i.e. texture, weight, friction, etc.). We believe that explanations of in-situ installations should not be via long texts or step-by-step explanations, but it should be obvious, easy to learn and derived from its own design, providing affordances for how to use in a public context. In heritage environments, such technology could physically stand in the way of experiencing the space, and sharing the use of the installation among visitors.

Interactive objects, including physical models in museums and heritage environments require robust forms of technology. Although the physical models were designed as hollow, we observed that participants touched the physical models only from outside by brushing the exterior walls with their fingers to feel the general shape of the building, but they only pointed at the elements on the inside from a distance. When we asked them about the reason during interviews, they admitted simply not having thought about touching the interior or being afraid to break some parts of the model. For more engaging role of the physical models, they probably should have been bigger and more robust, having more durable look to stimulate visitors to touch them and examine them from both inside and outside. Furthermore, physical models should not be simply stolen or damaged, and thus issues of cost and ease of replacement should be well considered [Marshall et al, 2016].

Based on our results, we realized that participants differed in the way of interacting with the installation. One category of participants were more focused on understanding the content and thus their interaction was a procedure to achieve this goal. Therefore, they tended to interact with the physical models in a chronological order starting from the 12th-century model to the 20th-century model. The different modalities might make it a bit more complex for visitors not accustomed to modern digital technology (i.e. elderly visitors), and influenced their exploration strategy. While the second category of participants, who have more digital expertise (i.e. students, architects and teachers), considered the installation as a game to play with, and then their understanding of the implied information comes along the way. They started to randomly place the physical models back and forth, and thereafter they tended to build their comparisons and interpretations about the content of heritage information. Accordingly, we believe that an equilibrium needs to be sought between the educational and entertaining role of the installations that meant to convey heritage information to lay visitors. Heritage communication might well be benefited by combining entertainment and informal education in a novel and non-didactic manner [Light, 1996].

5.6.5. Shortcomings and Limitations

We realize that the experiment of this study was deployed for a relatively short time, and the chosen case study has lightly colored interior walls, located in a small town. The subjective appreciations from interviews and UEQ might be too enthusiastic, as participants were aware this was explorative research. At the same time, because of the qualitative nature of the research, we believe that most of our findings and discussions can be generalized towards forms of interactive projection mappings in a heritage context.

In our installation, the length of the projector cable prevented a continuous 360° rotation, thus the cable occasionally got stuck or that participants had to rotate the projector back around in order to look at the other side. This may have influenced the experience, as participants felt they needed to be cautious and sometimes did not dare to move further when feeling any resistance. So that, a continuous rotation is recommended for future similar installations, or at least indicating the rotation range on the installation per se could be a handy solution.

Furthermore, according to the concept of participatory museum and connecting visitors [Simon, 2010], we believe that incorporating a TUI in our prototype with projection mapping might well increase interactions among heritage visitors who do not know each other to actively engage and to socially interact. However, due to the limited number of participants and the short time of the experiment, we only observed and mapped the discussion and social interaction among the visitors who knew each other in advance and arrived in groups (i.e. family visits or group of friends). Accordingly, we recommend that the influence of these kinds of incorporation of communication mediums should be further investigated on how they affect social interaction in heritage environments.

Since the function of the chapel changed over time, as it is no longer used for worship, projections might have been extended to also include the rituals during each time period beside the spatiotemporal transformation for more memorable and immersive visiting experience.

5.7. Conclusion

In this paper, through a field study in an architectural heritage environment, we deployed a mixed-method evaluation to investigate how projection mapping steered by a TUI enhances the communication of the spatiotemporal transformation of architectural heritage. The chosen case study is the Graethem chapel in Belgium, its history shows a very diverse building phases during its life time from the 1120s until the present.

Our findings show several qualities of using interactive projection mapping to communicate heritage providing an interactive experience. For instance, how the in-situ projection allows for exploring and comparing the existing situation of architectural heritage with previous building phases, and how it positively affects visitors' understanding and memorability of the aesthetic features of architectural heritage. We discuss the complementary role of the TUI in communicating the spatial features, and how the interplay between the two modalities enhances the communication of the spatiotemporal transformation of architectural heritage, and allows for more social interaction among visitors. We outline several design recommendations to overcome current usability issues about physical affordance, robustness and the entertaining role of design.

Chapter 6:
Neferirtenef Tomb-Chapel

6

This chapter has been submitted as:

Eslam Nofal et al. (under review). “Situated Tangible Gamification of Heritage for Supporting Collaborative Learning of Young Museum Visitors”, *ACM Journal on Computing and Cultural Heritage (JOCCH) [under review]*

Abstract

Museums offer an ideal environment for informal cultural learning on heritage artifacts, where visitors get engaged in learning due to an intrinsic motivation. Sharing the museum space among visitors allows for collective learning experiences and socializing with each other. Museums aim to design and deploy Tangible User Interfaces (TUIs) in order to embrace the physical materialities of artifacts in the visiting experience. TUIs are believed to be more collaborative, attract more visitors, and persuade them to explore further. Cultural learning on heritage artifacts is particularly meaningful from the early age when opinions and attitudes are shaped. Museums accordingly follow a gamification approach (i.e. using game elements in a non-game context) to provide a collaborative and entertaining learning experience to young visitors. In this study, we investigate the implications of merging these two approaches in order to take advantage of the qualities of both TUIs and gamification in an educational museum context.

Accordingly, we present *TouchTomb* and its evaluation in a real-world museum environment. *TouchTomb* is a *situated tangible gamification* installation that aims to enhance informal cultural learning for young visitors and to foster engagement and collaboration among them. The basis of the installation is a shared progress bar and three games with different spatial configurations, embedded into a custom fabricated replica of an ancient Egyptian tomb-chapel wall on a 1:1 scale. Our field study involved 14 school visits with a total number of 190 school pupils (from 10 to 14 years old). We deployed a mixed-method evaluation to investigate how such a tangible gamification approach entertains and educates 15 pupils collectively for a maximum of 15 minutes, including the evaluation procedures. We particularly investigated how the different spatial configurations of the game setups influenced the stages of pupils’ cultural learning, and the levels of engagement and collaboration among them. We conclude the paper by discussing the qualities of tangible gamification and its role in facilitating cultural learning. For instance, cultural learning is enhanced by situating heritage artifacts in the experience, and embedding learning in the reward system. Engagement and collaboration among visitors are fostered by creating a sense of ownership and designing a diversity of goals.

6.1. Introduction

The educational role of museums is crucial to communicate the vast amounts of artifacts' information to the general public [Hooper-Greenhill, 2013]. Museums are expected to broaden the general knowledge of their visitors during their visiting experience [Falk, 1998; Kelly, 2007]. Heritage museums therefore offer an ideal environment for informal cultural learning [Hein, 1998; Hooper-Greenhill, 1999; Falk and Dierking, 2002]. Cultural learning is described as the use of communication mediums for the acquisition of knowledge that encourages cultural awareness and appreciation [Ibrahim et al, 2015]. From related literature [Dierking and Falk, 1998; Ham, 2013], people who learn about cultural heritage are either obliged to learn due to educational requirements, or people who choose to learn for fun, or get engaged in learning due to an internal motivation. The latter denotes to 'informal cultural learning', where people are driven to pay attention and learn due to intrinsic motivation related to what they are hearing, seeing, reading, or doing [Ibrahim et al, 2015]. Museums offer a collective learning experience by sharing the space among visitors and socializing with each other depending on mutual interests [Simon, 2010]. It is widely admitted that establishing social relationships during informal learning processes is among the main expectations of museum visitors [Vermeeren et al, 2018].

Museum environments bring people into contact with original physical artifacts in a real scale and texture, enjoying their visible history. Heritage museum artifacts are rich in content and encompass several aspects of tacit knowledge which are relatively challenging to communicate due to their implicit character, such as architectural qualities, historical values and artistic features [Nofal et al, 2018.a]. Museums accordingly aim to design and deploy Tangible User Interfaces (TUIs) in order to embrace the physical materialities of artifacts in the visiting experience [Dudley, 2010]. TUIs are believed to be more collaborative, attract more visitors, and persuade them to explore further. The qualities of TUIs might well facilitate heritage communication in museums, such as requiring little experience or skills, performing better in terms of recalling information because it requires multimodal ways of human perception to discover and decipher their meaning [Seo et al, 2015], supporting collaborative and participative processes among users [Claes and Vande Moere, 2015; Not et al, 2019], and attracting more visitors towards more extensive forms of exploration during interactive exhibits [Ma et al, 2015].

Cultural learning on heritage artifacts is particularly meaningful from the early age when opinions and attitudes are shaped. Educating youngsters about heritage is challenging when linked to educational programs in schools due to lack of interest and protection issues. Young visitors constitute a significant part of museum visitorship, whose experience is considered as a powerful mediator of memory, enjoyment, and learning [Piscitelli and Anderson, 2001]. Young visitors gain understanding from their observations of, participation in, and reflection of a variety of social activities that derive from their physical interactions with museum artifacts [Henderson and Atencio, 2007]. For them, learning is intrinsically motivating when it is spontaneous. They are motivated to learn when they are involved in meaningful activities and experiential processes, meaning that their experience might well involve sensory and emotional faculties beside intellectual capabilities [Csikszentmihalyi and Hemanson, 1995]. Yet, museums face a challenge of offering a 'situated' environment by integrating various situations for learning into lifelong opportunities that reinforce each other [Paris, 1997]. These situations can be effective if they promote the motivational processes embodied in constructing personal meaning, making choices about goals and engagement, adjusting challenges, taking responsibility and control for self-directed learning, and collaborating for joint goals and teamwork.

According to the theories of cognitive development, young children benefit from learning that is organized as an interaction among peers 'collaborative learning' [Crook, 1998], which is believed to improve both learning outcomes and engagement [Nastasi and Clements, 1992]. Collaboration allows for co-constructions within collaborative problem solving, and enables children to articulate their thoughts publicly [Hoyles, 1985], which helps in bringing to consciousness their ideas that they are just beginning to grasp intuitively. Therefore, the gamification approach, which denotes to the application of typical game elements in non-game context, seems to be a promising solution in heritage museums for providing a collaborative and entertaining learning experience to young visitors. Although gamification aims to maximize enjoyment and engagement through capturing children' interest, inspiring them to continue learning in their contexts [Huang and Soman, 2013], most heritage game interfaces are technological in nature, and are not directly connected to the heritage context or content. For instance, gamification supports the learning of heritage through different techniques, such as serious games that can be played online [Froschauer et al, 2012] or running as a gamified smartphone application during the museum visit [Coenen et al, 2013], or even by combining gamification with augmented reality [Hammady et al, 2016].

Consequently, we introduce the approach of *situated tangible gamification* by embedding game setups with different spatial configurations into a TUI in order to enhance informal cultural learning and to foster collaboration and engagement of museum visitors. Through a field study in a real-world museum environment, we deployed a mixed-method evaluation to investigate how such a tangible gamification approach enhances the cultural learning of young museum visitors (10-14 years old) on an ancient Egyptian tomb-chapel exhibited in scale 1:1 at the Royal Museums of Art and History in Brussels. We particularly investigated how the different spatial configurations of the game setups influenced the stages of pupils' cultural learning, and the levels of engagement and collaboration among them. In particular, the following research questions are explored: (a) how do the spatial configurations of tangible gamification impact cultural learning of young museum visitors; and (b) how does the diversification of tasks augment social interaction and collaboration among them?

6.2. Related Work

6.2.1. Tangible User Interfaces (TUIs)

The research of tangible interaction tends to investigate how computational and mechanical advancements can be combined to allow novel forms of natural manipulation and full-body interaction with data and information [Hornecker, 2005]. In comparison to GUIs, tangible user interfaces (TUIs) are believed to be relatively more intuitive, as TUIs tend to communicate meaning through their physical affordances [Macaranas et al, 2012], such as by mapping information into physical shapes and forms, or into its material attributes (e.g., size, shape, texture, color, weight). Further, the embedded representation of information by giving the data physical form and blending it with physical environment is believed to be the most useful at human-accessible scales, where the physical size and distribution of the referents maximizes visibility and reachability [Willett et al, 2017].

TUIs applications in museums vary in terms of how the interface is situated in the context of the artifact; from less situated interaction when the original artifact is not exhibited at the museum [Nofal et al, 2018.a] or the interface and the artifact are located in distant places in the museum for provoking visitors' curiosity [Duranti, 2017], to a semi-situated experience, such as using a smartphone connected to a physical magnifying lens to examine museum artifacts and receive extra digital content on the smartphone [Van der Vaart and Damala, 2015], to more situated experience by using the original artifact as an interaction device [Not et al, 2019]. Accordingly, TUIs offer a spectrum of opportunities for museums with regard to the level of situatedness, and targeting specific audiences to communicate tangible and intangible heritage information. Further, the tactile qualities of tangible interaction allow for interactive installations in museums that target specific audience [Duranti, 2017]. For instance, the mix of materialities encourages creativity for children's playful exploration in museums [Taylor et al, 2015].

In general, the qualities of TUIs are used to promote learning activities, such as the use of physical materials to facilitate linking between perception and cognition [Marshall, 2007]. Likewise, three-dimensional forms are easier to be perceived through haptic rendering representations than through visual displays alone [Gillet et al, 2005]. The interlinks between physical actions and digital outcomes of TUIs might be particularly suitable for engaging children in playful learning [Price et al, 2003], while increasing the size of the TUI creates a shared space among users, allowing for collaborative learning [Suzuki and Kato, 1995].

6.2.2. Gamification to Support Learning

Educational games are believed to balance between entertainment and didactic objectives. There is a conceptual separation between the ideas of game and play. Games are seen as rule-bound, goal-oriented and finite, whereas 'play' implies freedom of choice and unbound exploration. *Gamification* is used to refer to the use of game design elements in non-game contexts [Deterding et al, 2011]. These game design elements include interface design patterns, such as the use of badges and leaderboards; gaming mechanics such as the use of time constraints and limiting resources; as well as more broadly, game design principles such as having to complete clear goals and receiving rewards.

To design a *gamified* experience, possibly in a heritage context, one needs to take into consideration a myriad of factors. A gamified interaction typically gives rewards and punishments as well as adds quantifiable constraints (i.e. time) while performing tasks thus creating artificial conflicts and consequently driving the players through a designed experience. Similar principles of gamified interaction also apply even for puzzle-like or collaborative games. In those cases the referred conflict simply gets transferred into a conflict between the player and the game rather than between players [Salen and Zimmerman, 2004]. Rewards for gamification are both immediate, i.e. receiving a coin for defeating an enemy in an adventure game (immediate goal) but are also overarching: the final quest that is only achieved by completing a series of intermediate goals. For instance, in a treasure hunt game design, with an overarching goal of exploring a full archaeological area, a series of 3D reconstructions of buildings are awarded to the participants as they achieve the intermediate goals of properly locating them [Sun et al, 2008].

When referring to education, the outcomes of a game need to be evaluated based on learning criteria. Though gamification is often employed in the education of children for its motivational affordances [Huotari and Hamari, 2012]. There has been critique for the imbalance of actual learning material and distractions from the non-educational, gamified elements [Andrade et al., 2016]. This balance however is not clear-cut. When compared with traditional (i.e. non-gamified) learning methods in respect to time to achieve progressive learning goals, the gamified approach starts with lower effectiveness (due to the need to adapt to the game itself) but then manages to retain the continuous engagement as time progresses and the learning goals evolve [Kim and Lee, 2015]. Gamification is also evaluated in its ability to inspire intrinsic instructional activities to children, namely learning when there is no external pressure from adults [Carvalho et al, 2015]. Gamification techniques have been used to bypass the perceived overall difficulty of tasks by gradually solving easier sub-tasks [Kim et al, 2018] and therefore maintaining the balance between challenge and skill. This provides a bridge between experiential learning theory [Kolb, 1984] and gaming, through the concept of learner or player ‘flow’ to describe a state in which a person has a good balance between skill and challenge [Kiili, 2005].

Gamified experiences do not need to be complete games but can contain only game elements. In heritage communication, informal cultural learning can be gamified in types such as: observation tasks; which stimulate spatial reasoning and contextualized search as in identifying parts of a painting, reflection tasks; which aim for synthesis of clues and past information through quizzes and arcade tasks; which stimulate fantasy as in ancient world simulation games [Bellotti, 2012]. The use of gamification in existing literature generally enhances learning [Hamari et al, 2014] and when referring to collaborative learning in particular, games have been identified for supporting exploration and helping to overcome group social conformity [Kim et al, 2018]. Nevertheless, there has also been criticism for its side-effects in collaborative contexts, such as the emergence of unwanted competition [Hamari et al, 2014].

6.3. Design and Development

In order to enable informal cultural learning for young museum visitors, and to investigate the influence of tangible gamification on their learning, we aim for a physical, immersive experience with real-life, human-scale artifacts of high cultural and historical value. In this section, we discuss the choice of the context and explain our design.

6.3.1. Context

Most ancient Egyptian antiquities are characterized by tacit knowledge like historical values as well as distinctive architectural qualities, which all are challenging to be conveyed to public visitors. We chose to communicate the tacit heritage knowledge of the *Tomb-chapel of Neferirtenef* (Figure 6-1.a and Figure 6-1.b) specifically because: (a) the original tomb is exhibited in scale 1:1 at the antiquity department at the Royal Museum of Art and History in Brussels; (b) its features are comprised of a rich variety of knowledge that could be communicated to visitors, and accordingly (c) it is valorized in learning plans for school visits, as the history of Egypt is part of their educational curriculum. As such, our study was deployed in close collaboration with the Antiquity Department of the Royal Museum of Art and History in Brussels. The museum possesses the largest collection of Egyptian antiquities in Belgium.

The tomb-chapel originates from the Memphite necropolis, in Saqqara and dates to the early 5th Dynasty (ca. 2494-2455 BC). It originally stood near the southeast corner of the funerary complex of pharaoh Djoser (3rd Dynasty, ca. 2667-2648 BC) in Saqqara. The monument is the largest ancient Egyptian work of art in Belgium, acquired in 1906 by curator Jean Capart. He had accepted the offer of Gaston Maspero, then director of the Department of Antiquities in Egypt, who hoped to counter the pillaging of the tombs in the necropolis by offering the major museums around the world the opportunity to acquire an entire monument for their collection [Van de Walle, 1978]. Ever since it was installed in the Brussels museum in 1907, the funerary chapel of Neferirtenef has been one of the most iconic works of art in the Egyptian galleries.

The chapel is part of a mastaba, a tomb for the elite consisting of a rectangular structure above ground and an underground burial chamber accessible via a vertical shaft. Offerings for the deceased could be placed in the tomb-chapel, which is part of the above-ground building [Van de Walle, 1978]. Neferirtenef's name is mentioned on the walls and he is represented, together with his family, on the wall reliefs that also show offerings and goods being brought by retainers. The west wall includes two false doors, essential features in Egyptian tombs: these are stone doors through which the spirit of the deceased could pass, in order to receive the sustenance offered to him by relatives in the chapel.

(a) (b) (c)

Figure 6-1: *Tomb-chapel of Neferirtenef: (a) the exterior of the tomb-chapel as installed at the Royal Museums of Art and History in Brussels, (b) the interior West wall of the chapel, and (c) the selected part of the wall relief that contains different types of tacit knowledge.*

Consequently, we organized a 2-hour co-design workshop with 3 heritage professionals (2 males, 1 female), consisting of one museum curator and two academic researchers in Egyptology. The workshop was conducted to define: (a) what specific information the museum wishes to communicate to visitors; (b) what kind of visitors are more interested in the Egyptian collection, and the tomb-chapel in particular; and (c) what kind of installations that can be used in the museum context. We found that young visitors (10-14 years old) are the most visiting category to this tomb-chapel due to the direct link to their educational curriculum. They come in groups as guided school visits, having limited time to visit the entire Egyptian galleries. The workshop concluded by selecting a section of the internal west wall of the tomb-chapel (Figure 6-1.c) because its decorations contain three types of tacit knowledge of Egyptian built heritage:

- ***Architectural qualities:*** The tomb-chapel has one real door and two false-doors. The false-door is considered a threshold between the worlds of the living and the dead, their spirit can enter or leave the grave. A rolled-up reed mat is hanging above a doorway (both real and false doors), which is very recognizable in ancient Egyptian architecture, it is symbolically in stone in the tomb-chapel.
- ***Historical values:*** In ancient Egypt it was customary to bring different types of offerings to the deceased in the tomb-chapels. Drawings on the wall represent these offerings, as if the deceased would be able to receive them forever.
- ***Artistic features:*** Like in any ancient Egyptian art, men were painted in reddish brown because they were exposed to the sun due to their outdoor activities, while women were painted in yellow beige because they were responsible for indoor activities. Thus, gender could be determined at a single glance.

6.3.2. Conceptual Design

We present *TouchTomb*, a tangible gamified installation that facilitates the communication of tacit knowledge of the Neferirtenef tomb-chapel in an informal cultural learning setup. As part of our design requirements, the installation needs to engage one guided school visit, which consists of approximately 15 pupils that are between 10 and 14 years old, for a maximum of 15 minutes. To allow for the appropriate evaluation methods to be subsequently deployed, these constraints mean that an extreme short time span is dedicated to the actual engagement with the installation.

We built a physical, life-sized replica wall of the chosen section of the interior west wall of the tomb-chapel as an interactive, tangible interface. The wall was deliberately positioned just outside the original tomb-chapel as shown in Figure 6-2.a. The wall hosted three distinct game setups. Each game setup was specifically designed to communicate a specific type of tacit heritage information: architectural, historical, and artistic (as explained in Section 6.3.1). While each of the games consisted of reaching a specific goal, their progress was explicitly shared with the pupils of all the games by way of a common progress bar. The strategy of separating pupils into three collaborative groups that compete in parallel enabled smaller group sizes and different spatial configurations of the game setups.

Each game setup was introduced by a question plate that was located in the middle of the wall with a distinct color for each game setup. A light-emitting bar graph conveyed the progression of solving each of the games. Each game was based on two distinct reward systems. When completing an intermediate goal a partial reward was given by adding a light to the progress bar. Once the progress bar was fully-lit, meaning all intermediate goals are completed, a grand reward was given to denote the end of the game. In practice, this means revealing extra information corresponds to the game setup by rotating the question plate 180° (Figure 6-2.c). As the back of the question plate contained textual information that explained the answer of each of the questions[1].

(a) (b) (c)

Figure 6-2: *TouchTomb: a replica wall in scale 1:1 of the chosen section of the interior west wall of the tomb-chapel: (a) its location outside the tomb-chapel, (b) a close-up view of the installation, showing the three games, and (c) rotating the question plate to reveal extra information when the game is solved.*

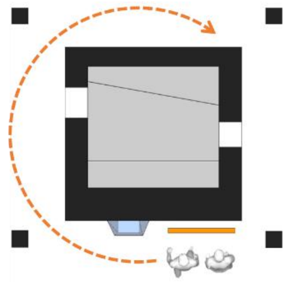
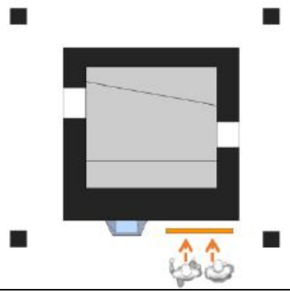
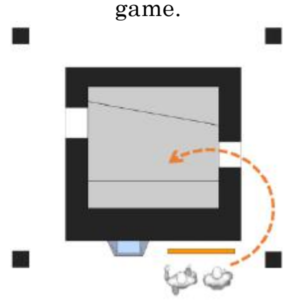
6.3.3. Game Setups

The three game setups (Figure 6-2.b) are coined as: '*around' exploration, 'in front' interaction* and *'inside' navigation,* as they were purposefully designed around three

[1] A video showing *TouchTomb* and the overall experiment is available on: https://vimeo.com/336827694

different spatial configurations to investigate how these configurations impact interaction with tangible and real-life interface, as shown in Table 6-1. In the *'around' exploration* setup, visitors are expected to solve a 3D puzzle and to explore where it fits in the tomb-chapel. The semi-situated interface of the *'in front' interaction* setup, consisted of the replica wall of the tomb-chapel that provides visitors with familiar physical objects and actions. The *'inside' navigation* setup embraced a fully situated interface that required a direct interaction with the original tomb-chapel, which becomes the output medium as the interface becomes embodied by the physical shape and materiality of the artifact itself.

Table 6-1: *Comparison between the three game setups of TouchTomb.*

	'around' exploration	***'in front' interaction***	***'inside' navigation***
Game setup	Exploring the tomb all around to solve the game. 	Interacting only in front of the wall for solving the game. 	Navigating inside the tomb to find hints for solving the game. 
Challenge	Solving 3D puzzle that represent the rolled-up reed mat at the top of the false door. 	Sorting magnetic cards for the different types of offerings in ancient Egypt. 	Mapping coloured cards to the human figures according to the corresponding painted colours. 
Final reward: cultural learning	*Architectural qualities:* Learning about the false-door in the ancient Egyptian architecture. 	*Historical values:* Learning the different types of offering in ancient Egypt. 	*Artistic features:* Learning the role of color in the ancient Egyptian art. 

6.3.3.1. 'around' exploration

The *'around'* game setup urges visitors to solve 12 pieces of a 3D puzzle on a custom-designed platform located on a table beside the tomb-chapel, to locate the result on *TouchTomb* where they think the result belongs, and to find another example of the puzzle result, and thus they are stimulated to explore the monument all-around.

We chose the semi-cylindrical top of the false door as the puzzle detail, which represents, in stone, a rolled-up reed mat. As a constraint, the puzzle has to be solved on a custom-designed platform. When all pieces are in place, a LED strip lights up around the puzzle pieces as a reward (Figure 6-3.a). Then, by exploring the tomb-chapel, visitors were expected to discover that the location of the rolled-up reed mat above the false door as well as above the real door, thus by analogy the closed, false door was also considered as a passageway (for the soul of the dead). Further, when the platform is hung on the replica wall, the 12 LEDs on the progress bar of the first game light up, revealing extra information on rolled-up reed mat of the false-door.

6.3.3.2. 'in front' interaction

The *'in front'* game setup stimulates visitors to stand in front of *TouchTomb* in order to search and map 12 offering cards to the corresponding craved onto the replica wall. Each card has a specific icon of one of the main offering types in ancient Egypt (Figure 6-3.b). In total there were 4 meat, 4 bread and 4 fruit cards. Visitors were expected to sort the cards by placing them to the corresponding drawings on the replica wall. One LED lights up in the progress bar for each valid placement. When all cards are correctly placed, extra information is revealed to inform them that those drawings on the wall represent offerings in ancient Egypt, namely that the deceased would be able to receive them forever.

6.3.3.3. 'inside' navigation

The *'inside'* game setup requires visitors to go inside the original tomb-chapel to examine which human figure is painted in which color. Visitors are given 12 gender cards, each card has a specific color for the painted human figures on the original wall (Figure 6-3.c). In total they were given 5 yellow beige and 7 reddish brown human figures. They were expected to place the cards on the corresponding human figure on the replica wall according to their colors. Similar to the previous setup, one LED lights up in the progress bar for each valid placement. When all cards are correctly placed, extra information is revealed to explain the role of color in ancient Egyptian art and how easy the gender could be determined at a single glance.

6.3.4. Technical Development

TouchTomb was fabricated to simulate the original wall of the tomb-chapel within obvious constraints of financial costs and robustness. The overall dimensions are 180 cm width and 240 cm height, comprising 5 panels of MDF wood that are attached together with metal supporters. In the middle of the wall (i.e. false-door). The progress bar consisted of a LED strip, and connected to an Arduino Mega in the backside of *TouchTomb* to control six Servo motors for rotating the three plates of questions (i.e. two motors for each), as shown in Figure 6-2.c.

In the *'around'* game setup, we replicated in scale 1:1 the reed mat by 3D printing 12 jigsaw puzzle pieces in a semi-translucent white polymer, the prominent pieces were then colored in gold to stand out (Figure 6-3.a). The custom-designed platform has an Arduino Mega integrated with 12 LDR light sensors to detect each of the puzzle pieces and to illuminate the LED strip. All puzzle pieces have an integrated magnet to stick to the platform, and the platform has four strong magnets from the backside, so that it could be hung vertically to the *TouchTomb* in its corresponding location. For both the offering cards of *'in front'* game and gender cards of *'inside'* game, each card has 3 magnets from the back side with an integrated electronic circuit that is consistent for each offering category (Figure 6-3.b), and for each gender category (Figure 6-3.c). Cards were not unique, meaning that for example any fruit card in *'in front'* game fits with any fruit-drawing, and any dark card in *'inside'* game fits with any man-figure on the wall. For the sake of physical affordance, we engraved the outlines of all cards to be aligned on *TouchTomb*, we also considered the issues of cost and ease of replacement by producing more spare cards.

Since the original tomb-chapel is exhibited in a national museum, all object labels and gallery texts needed to be presented in the two main official languages (i.e. French and Dutch). Accordingly, we custom designed the interface of *TouchTomb* to support as many languages as needed, by allowing the explanatory plates to be easily removable and exchangeable by means of magnetic attachments (Figure 6-3.d).

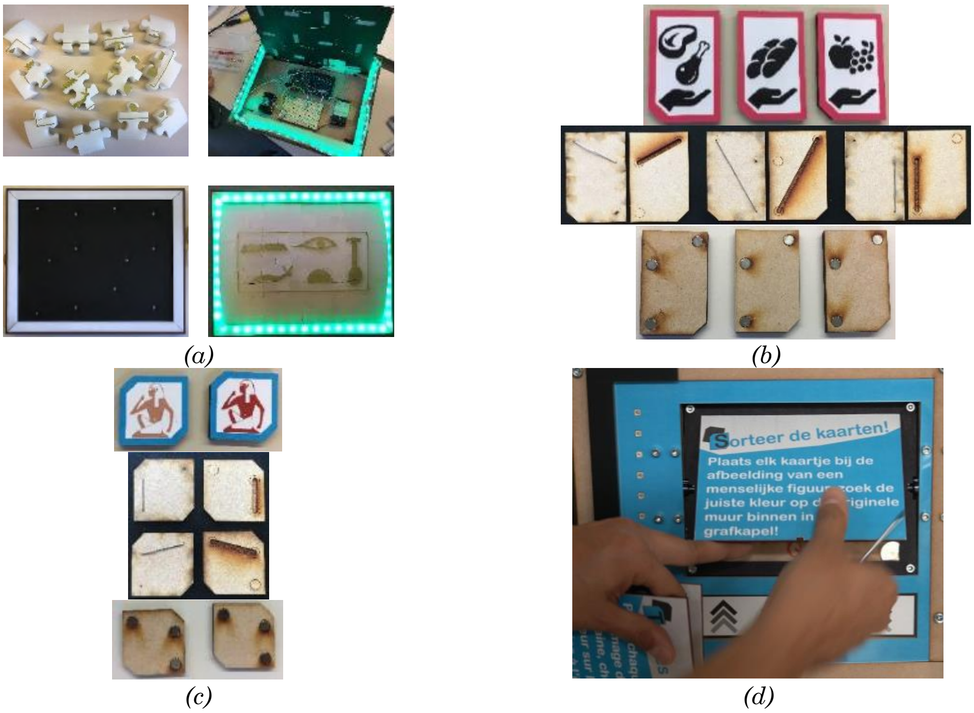


Figure 6-3: *Technical installation: (a) puzzle pieces with integrated magnets, wiring inside the platform of sensors and LED strip, custom-designed platform with the 12 light sensors, and the LED lights up when all pieces are correctly placed, (b) offering cards: front sides, wiring from inside, and magnets on the back side, (c) gender cards: front sides, wiring from inside, and magnets on the back side, and (d) the multi-language interface by changing one of the magnetic plates from 'Dutch' to 'French' according to the participating group.*

6.4. Methodology

6.4.1. Evaluation Methods

The evaluation study deployed a mixed-method methodology. A complete list of the scheduled school visits for Egypt galleries for the months of October and November 2018 was provided by the museum. Then, we asked the public service of the museum to recruit certain school visits based on their age category, mother tongue language, and time of visit. After giving a short-guided tour to each school visit about the general historical background of the tomb-chapel, we commenced the experiment with briefing the pupils about how they were expected to interact with *TouchTomb*. We asked teachers or guides to divide the pupils into three equal groups. Each group was assigned to a game setup, thus ensuring that each visit took part in all three setups mentioned above. The evaluation consisted of observing all interactions with *TouchTomb* and each other, a short semi-structured interview that focused on cultural learning, and a collaborative user experience questionnaire that captured the overall experience of the pupils. We obtained a permission to conduct the study (Key G-2018 04 1213) from the Ethical Commission of KU Leuven.

6.4.1.1.Observation

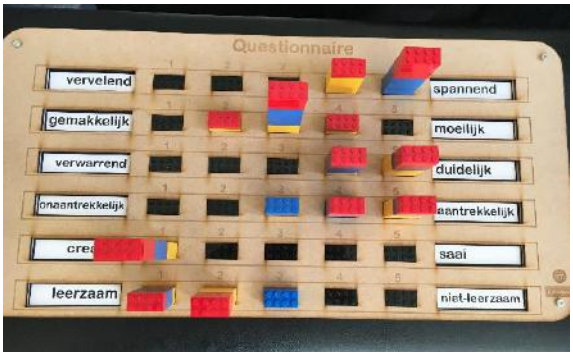
All pupils' interactions were observed and video-recorded, and then manually listed and analyzed in an Excel spreadsheet. The causal aspects of situatedness where captured by observing whether, when and which groups went inside the original tomb-chapel, and how this steered their game-solving and according learning activities. We manually noted all relevant collaborative and social interactions among groups, such as via talking (e.g. reviewing or guiding each other), or via actions (e.g. solving together or dividing the tasks among themselves). Further, we combined the durations of each game together with the human behaviors to determine the overall usability, such as whether the pupils easily understood the game rules and whether they paid attention to the progress bar.

6.4.1.2.Interviews

Both pupils and teachers were invited to partake in a concise structured interview that was audio-recorded. After the experimental phase of the study, we invited pupils of the three teams to partake in three structured and audio-recorded group interviews. Concretely, pupils were tested whether they acquired the intended cultural learning (Table 6-1) by way of open-ended questions: (a) in the *'around'* game, pupils were asked about the meaning of the false-door in the ancient Egyptian architecture, what is hanging above it, and whether there were similar places around or in the tomb-chapel; in (b) the *'in front'* game, about the main categories of offering in ancient Egypt, and what those offerings mean; and in (c) *'inside'* game about the colors of human figures in Egyptian paintings, and what those colors meant. The interviews polled about the pupils' appreciation of the experience and whether they preferred to try it alone, with family, or with school. Although teachers did not interact with the installation, they form a major stakeholder in reaching the learning objectives and in acting as a critical witness from a third-person perspective. Accordingly, we invited teachers to a concise semi-structured interview, which focused on their impression and appreciation for these kinds of installations, in an attempt to open up their critical view towards more subjective answers and suggestions.

6.4.1.3.User experience questionnaire

The interviews were followed by a novel user-experience questionnaire (UEQ) that measured in a collaborative and engaging manner how the experience of the pupils was enjoyable, easy, clear, attractive, creative, and informative. The questionnaire was designed as a tangible extension of the game experience by using physical game objects (i.e. LEGO® blocks) that could be placed on a 5-point Likert scale, from -2 (representing the most negative answer) to +2 (representing the most positive answer), with 0 as the neutral answer. The three used colors of the blocks corresponded each to a unique game setup (i.e. yellow for *'around'*, red for *'in front'*, and blue for *'inside'*). Each pupil was handed six blocks in the corresponding color to answer the six questions in the questionnaire (Figure 6-4.b). The language of the questionnaire could be easily switched by replacing an underlying sheet of paper, as shown in Figure 6-4.a.



(a)

(b)

Figure 6-4: *A tangible gamified user-experience questionnaire using LEGO® blocks: (a) the custom designed questionnaire, and (b) a group of pupils collaboratively evaluating their experience (i.e. yellow for 'around' game, red for 'in front' game, and blue for 'inside' game).*

6.5. Results

The study involved 14 school visits with a total number of 190 school pupils, both Dutch and French speaking from all over Belgium. We categorized our results into two sections: (a) how the three spatial configurations of *TouchTomb* impacted the stages of pupils' cultural learning about architectural, historical and artistic information of the tomb-chapel; (b) how pupils appreciated the overall user experience, and how the design of a tangible game in a scale 1:1 encourages them to collaborate, spatially as well as socially.

6.5.1. Situated Cultural Learning

Our results on cultural learning are adapted from Kolb's model of experiential learning [Kolb, 1984]. This model has been increasingly popular in museum interpretation and education programs [Sitzia, 2016], as it frames the process of knowledge creation through the transformation of experience, starting from how pupils have a concrete experience (doing), followed by a reflective observation (reflecting) and an abstract conceptualization (conceptualizing), and ending with the active experimentation of the knowledge they gained (applying) by empirical testing the implications of the seen concepts. Accordingly, the three game setups distributed the learning cycle of young visitors in terms of how they occurred in space (Figure 6-5) and time (Figure 6-6) in significantly differing ways.

In general, the learning stages of the *'around'* game setup were spatially dispersed between the table to the tomb-chapel passing by the replica wall, and temporally sequential with several gaps in-between. While, the learning stages were more clustered in the *'in front'* game setup in both space and time, occurring in front of the replica wall and overlapping in time. In the *'inside'* game setup the learning stages were spatially contained in front of the replica wall and inside the tomb-chapel, and temporally intermittent, meaning that learning stages were not always continuous.

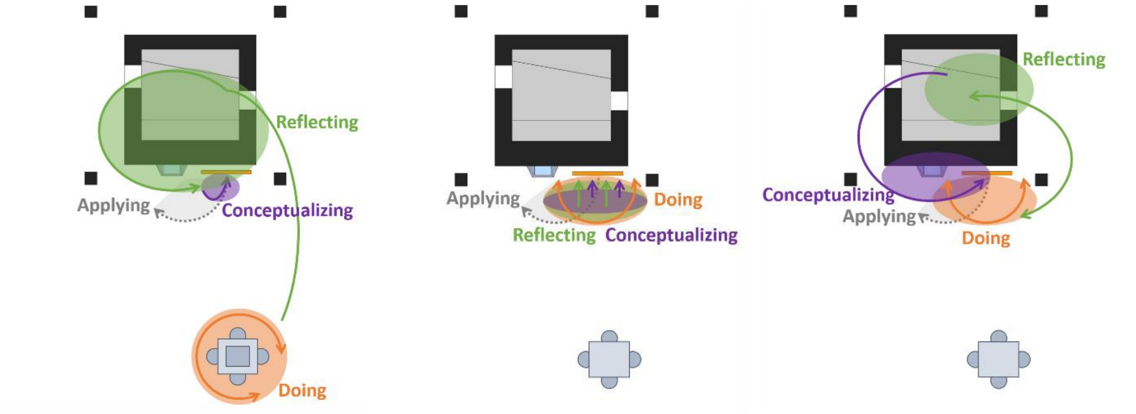


Figure 6-5: *Spatial distribution of the four learning stages for the three game setups: (a) dispersed in the 'around' game setup, (b) clustered in the 'in front' game setup, and (c) contained in the 'inside' game setup.*

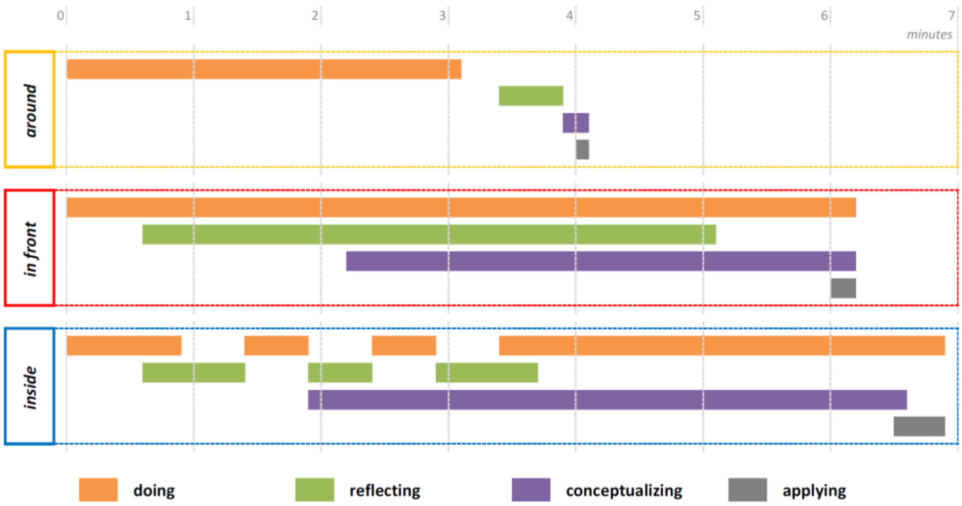


Figure 6-6: *Timeline of the four learning stages for the three game setups (average of the 14 school visits): sequential in 'around', clustered in 'in front', and intermittent in 'inside'.*

In the *'around'* setup, learning stages were affected by the spatially dispersed tasks between the table to the tomb-chapel passing by the replica wall. All groups started with the 'doing' stage by solving the puzzle on a table that was relatively far from the context (Figure 6-5.a), where they considered it only as a game with no link to the context (i.e. tomb-chapel). The implied physical and scale relationship was not obvious, which made them asking what to do after solving the puzzle, although they all read the question on the interface. After a time lag, they went inside the tomb-chapel to compare their solved puzzle to the inscriptions on the wall 'reflecting'. Subsequently, they managed to place the solved puzzle above the false-door on the replica wall 'conceptualizing'. Although almost all groups (N=13) managed to answer the question of the meaning of the false-door in the ancient Egyptian architecture *"dead people can go through this door to the second life"* (participant 9), only half of the groups (N=7) knew that the piece above the door (i.e. result of the puzzle) represents the name of the tomb-owner in hieroglyphs. That might well be the result of the crowdedness and thus not watching the revealed information after placing the puzzle on the replica wall, or because of the ergonomics issue that the plate of the question is very low in relation to the puzzle spot. For each group, we had to explicitly ask pupils to look at the flipped question plate (i.e. the grand reward), or the teacher had to explain the information to the entire group (Figure 6-7.a). Almost none of them were able to mention the rolled-up reed mat above the real entrance of the tomb, but only few of them (N=3) mentioned the second false door inside.

In contrast, the learning stages of *'in front'* setup were more clustered and occurred only in front of the replica wall with several time overlaps (Figure 6-5.b). Pupils started to place their first offering cards on the wall in a meaningless pattern 'doing', just to check if there is a LED lights up in the progress bar. Since pupils kept an eye on the progress bar to make sure whether their answer was right or not, they started to 'reflect' on the icons on cards and link them to the drawings on the wall; *"this is not fruit, we should place a meat card"* (participant 4). The stage of 'conceptualizing' occurred when they associate the question about offerings to the actions they were doing. While the stage of 'applying' came after solving the game and the offerings' information is revealed to them, as several groups were asked by teachers to read out loudly the revealed information to the colleagues (Figure 6-7.b). Time correlation between the learning stages influenced how pupils answered the learning questions in the interview. All groups (N=14) managed to answer the question of mentioning the main categories of offering in ancient Egypt. Many of them (N=9) were able to answer the second part of the question (i.e. the meaning of the offering) using their own words *"gifts to the dead people to have a good life in the other world"* (Participant 13). The remaining groups either they did not answer that part or they answered it wrongly based on their imagination *"vitamins for ancient Egyptians"* (participant 15), meaning that they less cared about the textual information.

The learning stages of *'inside'* setup were contained and achieved in multiple spatial zones, and temporally intermittent, meaning that learning stages were not always continuous (Figure 6-5.c). Pupils started with placing the gender cards on the wall without understanding what they mean 'doing'. Reading the question carefully, they realized that they have to go inside the tomb and look at the original wall, thus they recognize that colors on cards mean figures' colors on the wall 'reflecting'. By going forth and back from the replica wall to the original wall inside and by keeping an eye on the progress bar, they understood that dark colors mean men and light colors mean women 'conceptualizing'; one pupil was shouting to her colleague *"I found a man here, give me a man card"* instead of *"a dark card"* (participant 3). After solving the game and more information is revealed to pupils on the paintings in ancient Egypt 'applying', they seemed to have an intrinsic motivation to read the information that has been revealed (Figure 6-7.c). In this setup, the learning stages were contextually and timely interrelated, which positively affected the learning of pupils. All groups (N=14) managed to answer the question of the meaning of color in the Egyptian paintings. The majority of them (N=11) were even able to answer the 'Why' part of the question by recognizing that the dark color corresponds to men because they were exposed to the sun due to their outdoor activities, while the light color represents women because they were responsible for indoor activities.

(a) (b) (c)

Figure 6-7: *The grand reward of the game represents the 'applying' learning stage for the participants (a) a guide explains the revealed information to the entire group after solving the 'around' game, (b) a participant from 'in front' game is asked by the teacher to read out loudly the revealed information to his colleagues, and (c) a participant from 'inside' game read out loud the information that has been revealed after solving the game.*

In general, participants of *'inside'* and *'in front'* games found the experience very informative (69% and 67% respectively) compared to the pupils' answers of *'around'* game (52%), as illustrated in Figure 6-8. We assume that *'around'* game might well be less informative because of (a) the decontextualized setup of this game, as the table was not directly connected to the tomb, (b) the final reward of this game was not easily visible to pupils due to crowdedness and ergonomics, and (c) the information content might be a bit harder to convey, unlike the familiar types of offerings (i.e. *'in front'* game) and the colors of paintings (i.e. *'inside'* game).

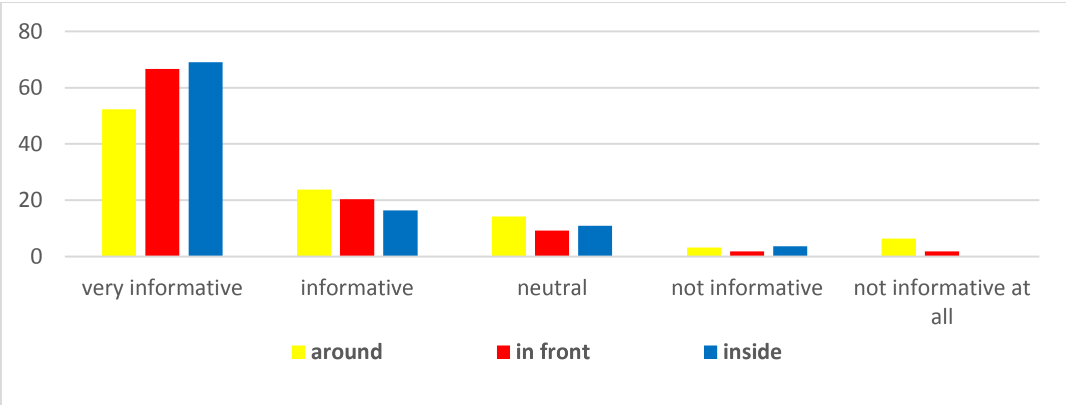


Figure 6-8: *Percentage of pupils' answers on how their experience was informative from the three game setups.*

6.5.2. User Experience

In this section, we report on the user experience in terms of their types of collaboration and social interaction, their forms of engagement and appreciation, the impact of game elements on their experience, and their replies on the user experience questionnaire.

6.5.3. Collaboration and Social Interaction

All participants stated that they prefer not to have this experience individually but in groups: 75 % with school-mates, and 25% with family members (e.g. siblings or cousins). Table 6-2 shows how each of the three game setups supports specific types of collaboration among pupils. Differences among the setups were clearly noticed in the certain collaboration types such as encouraging, dividing tasks and competing other teams, while the setups were almost similar in reviewing, guiding, and solving together:

Table 6-2: *Types of collaboration among participant groups (N=14).*

	'around' **game setup**		***'in front'*** **game setup**		***'inside'*** **game setup**	
Reviewing (n, %)	9	*64%*	7	*50%*	7	*50%*
Guiding (n, %)	7	*50%*	5	*36%*	4	*29%*
Solving together (n, %)	14	*100%*	12	*86%*	13	*93%*
Encouraging (n, %)	**7**	***50%***	3	*21%*	3	*21%*
Dividing tasks (n, %)	**6**	***43%***	2	*14%*	**7**	***50%***
Competing with other teams (n, %)	3	*21%*	**7**	***50%***	**6**	***43%***

Reviewing each other's answers in the three game setups occurred particularly in the 'doing' learning stage, such as when pupils determined whether puzzle pieces are correctly placed in *'around'* game, or whether the cards were true or false in both *'in front'* and *'inside'* games.

Guiding each other by showing one of the correct answers particularly occurred when someone was struggling, such as not knowing where and how to place the cards.

Solving together occurred in *'around'* game only during the 'doing' learning stage by gathering together to solve the 3D puzzle (Figure 6-9.a). While, it was extended in the other setups to include further learning stages, such as during 'reflecting' stage by checking together at the progress bar (Figure 6-9.b), and during the 'conceptualizing' stage by switching cards with learning names among themselves (Figure 6-9.c).

(a) *(b)* *(c)*

Figure 6-9: *Pupils are collaborating to solve the games in groups: (a) several hands in 'around' game are solving together the 3D puzzle in the 'doing' stage, (b) a group from 'in front' game during the 'reflecting' stage let someone placing the cards, while another one checking the progress bar, and (c) a girl from 'inside' game during the 'conceptualizing' stage is switching a man-card with her team-mate from one side to the other side of TouchTomb.*

Encouraging each other was only noticeable in *'around'* game when a certain pupil is encouraged to get engaged when seeing part of the result appears (i.e. hieroglyphs), and actively collaborates with peers. In contrast, participants of *'in front'* and *'inside'* games were all given cards in hands, so they felt compelled to be engaged from the beginning.

Dividing tasks is obvious in *'around'* and *'inside'* games because these two setups implicitly encouraged pupils to divide tasks among themselves. For instance, in *'around'* game one pupil is always responsible of holding the result piece of the 3D puzzle, while others look either inside or outside the tomb-chapel for the location where to place that result (Figure 6-10.a), and in *'inside'* game participants tended to assign the responsibility of checking the original colors of the human figures inside the tomb-chapel to some of them (Figure 6-10.c). While, we noticed dividing the tasks in *'in front'* game only when a tall boy was responsible of solving the high cards that his peers could not reach (Figure 6-10.b).

Competing with other teams was not intended in our design, there was no mention of time-tracking, speed or any other explicit indicator that would imply a competition between groups of different parallel games. Nevertheless the fact that the three games were solved simultaneously by the three teams created a kind of competition around the different groups. That was more noticeable among the teams of *'in front'* and *'inside'* setups because they were sharing the same space, looking at the shared progress bar; *"only three are remaining!"* clearly indicating a comparison and assumed pressure of being left behind.

(a) (b) (c)

Figure 6-10: *Participants are dividing the tasks among themselves: (a) a girl from 'around' game was holding the result piece of the 3D puzzle, while another girl was realizing and pointing to the location on TouchTomb where to put this result, (b) one tall boy from 'in front' game who was responsible of solving the high cards, and (c) two participants from 'inside' game were responsible of going inside the tomb-chapel to check the original colors of the human figures.*

6.5.4. Engagement and Appreciation

In general, participants of *'around' game* spent less time interacting and solving the game (4.1 minutes, avg; 4 minutes, median) in comparison to the participants of *'in front' game* (6.2 minutes, avg; 6.3 minutes, median) and *'inside' game* (6.9 minutes, avg; 7.3 minutes, median). We believe that the idea of having a centered-goal (i.e. solving the puzzle on a table) accelerated solving the game compared to the other games, where pupils were interacting in front a much bigger interface (i.e. *'in front' game*) or even physically going forth and back inside the tomb-chapel (i.e. *'inside'* *game*). Time was also an indicator of engagement that drove pupils to unintendedly take several weird postures, such as tiptoeing to reach the high cards (Figure 6-11.b) bending down to place the low cards (Figure 6-11.c), or sitting on the table while solving the puzzle.

(a) *(b)* *(c)*

Figure 6-11: *Engagement drove participants to take weird postures while participating: (a) three hands from* 'around' *game on the same piece of puzzle, (b) a pupil from* 'in front' *game tiptoes to put the card in place, while others are checking the progress bar, and (c) participants from* 'inside' *game were bending down to place the low cards.*

In general, the experience of tangible gamification seemed to be well appreciated by participants of the three game setups and their teachers as well, as demonstrated in percentages of each level of appreciation in Figure 6-12. All the interviewed teachers appreciated (i.e. 54% like it very much, and 46% like it) the approach of tangible gamification as an interactive educative tool in the museum context; *"I like it because they gain knowledge after interaction, I believe they will remember something from their interaction"* (teacher of Participant 9). They also liked it because children interacted in groups and because of the creativity features.

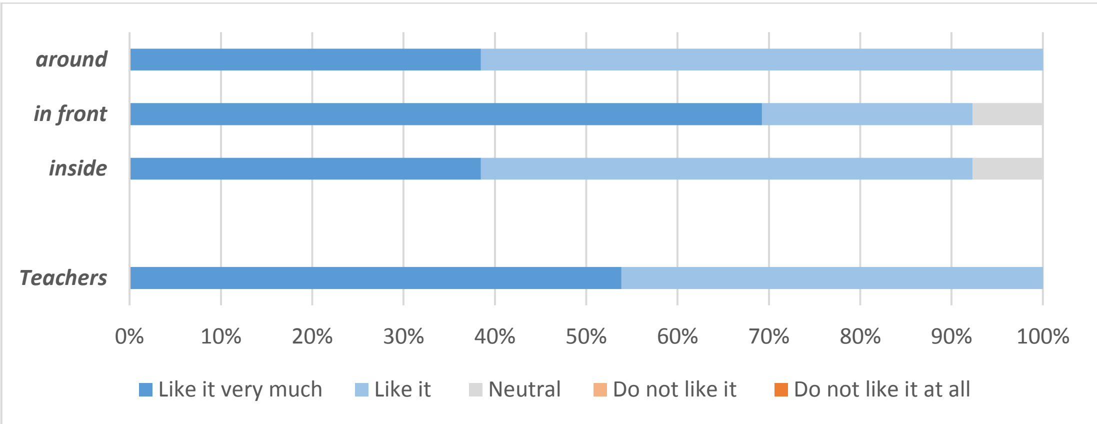


Figure 6-12: *Percentage of participants with each level of appreciation for the three game setups and teachers as well.*

6.5.4.1. Impact of gamification on user experience

We noticed that even after we explained the game objectives, there were situations that certain children did not know how to reach them, namely they did not understand the rules of the game. Consequently, we noticed those children learned the rules from their peers by looking and mimicking their actions, such as how to place the cards in *'in front'* game, and where to check the original colors in *'inside'* game. This type of mimicking was noticed in the space in front of *TouchTomb* even while an incorrect original understanding from one of them spread to the team (e.g. placing cards in mismatching locations).

The progress bar acted as a multifaceted game element driving their participation and transferring them from 'doing' to 'reflecting' learning stage, since pupils kept an eye on the progress bar to make sure whether their answer was right or not. The grand, overarching reward of our game design was meant to impact the learning of pupils, as discussed in Section 6.5.1. On the other hand, the gradual, intermediate reward system directly impacted the user experience. In general, pupils were getting excited when they were rewarded (i.e. having a LED lights up). Their excitement was observed individually via happiness facial expressions, verbal expressions *"oh, yes!"*, or even collectively via clapping to themselves. Some pupils were simultaneously looking at the bar when they were placing their own cards (Figure 6-13.a), while other pupils were dividing the tasks among the group as someone was placing the card and another one was checking the progress bar (Figure 6-13.b). The progress bar was also used as a check technique for the final result and to realize wrong answers, such as placing all cards but not having all the LEDs lighted on the bar, so pupils reviewed their answers and partially re-solved the game.


(a)


(b)

Figure 6-13: *Progress bar as a core element of the game (a) an individual simultaneous look at the bar while posting cards, and (b) a collaboration among the team: one is posting the card, while another one is checking the progress bar.*

6.5.4.2. User experience questionnaire

All the items of the user experience questionnaire are positively rated from the pupils of the three game setups (Figure 6-14). The results are formed by a common consensus that all the three game setups were creative and enjoying, and on the same level of clarity. The *'around'* game is rated as the least informative setup, which conforms to the learning results and the causes in Section 6.5.1, while pupils found the same game setup as the most attractive because of the luminous puzzle that visually stood out on the wall. The results of easiness seem to correlate with the duration of each game setup, and how the different learning stages were interwoven (Figure 6-6), so that *'around'* setup is rated as the easiest setup, then *'in front'* and lastly *'inside'* setup.

In general, participants enjoyed answering the questionnaire, we never encountered pupils who refused to participate, but they were jostling each other to receive their LEGO blocks. Due to the limited space around the questionnaire board, they participated team by team, meaning that teams could see answers of previous teams. Teachers explained the questionnaire to pupils and clarified the meanings of difficult terms (e.g. 'aantrekkelijk' in Dutch and 'attrayant' in French). Although they understood the objective of the questionnaire, they were playing with the LEGO blocks to physically build their own column charts (Figure 6-4). Pupils tended to loudly express their choices *"I find it very creative"* (Participant 1, *'inside'* team), or *"I think it was a bit easy, but very clear"* (Participant 11, *'in front'* team). Thus, participants were influencing each other in answering the questionnaire not only by seeing the answers of other participants, but also by encouraging each other to choose a specific answer. Similar to their game experience, mimicking each other to learn the rules applies here as well by looking at their peers or asking them.

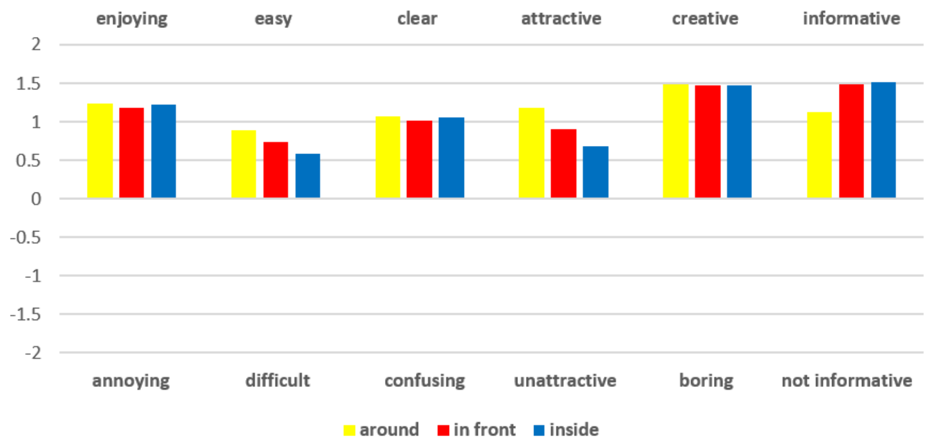


Figure 6-14: *Results of the user experience questionnaire ranging from very positive (2) to neutral (0) and very negative (-2) for the different items (yellow for* 'around' game*, red for* 'in front' game*, and blue* for 'inside' game*).*

6.6. Discussion

In this section, we discuss the implications of the results with relevance to future research or potential further developments of tangible gamification in a museum context. We outline several design recommendations based on the qualities of tangible gamification and its role in facilitating cultural learning.

6.6.1. Situated Tangible Gamification Influences Cultural Learning

The stages of visitors' cultural learning are influenced by the level of situatedness of heritage artifacts in tangible gamification.

Situated communication is denoted on how the information relies on the "physical context" to be understood [Rekimoto et al, 1998]. In heritage communication, the degree of situatedness influences understanding and experiencing heritage artifacts [Nofal et al, 2017.c]. Our results showed how situating the heritage artifact in the spatial configuration of each game setup influenced how, where and when pupils gained the knowledge. The heritage artifact was obviously contextualized in the 'doing' learning stage in both *'inside'* and *'in front'* game setups, as participants were either directly interacting with *TouchTomb* (i.e. replica wall) or compelled to enter the original tomb-chapel at the beginning of their interaction. While participants of *'around'* setup were not spatially connected to the heritage artifact in their first stage of learning (i.e. doing), and thus they were only playing to solve the puzzle. Further, the remote table of the puzzle decontextualized the learning process, creating a gap between the 'doing' and 'reflecting' stages, and thus delaying their 'conceptualizing' stage, as illustrated in Figure 6-6. Further, the spatially dispersed tasks caused frustration among the pupils, as they had to walk first to the *TouchTomb* after solving the puzzle, then to explore the original tomb, and to return back to *TouchTomb*. As a result of the sequential process of learning and the spatially dispersed tasks, *'around'* game was the least informative setup (Figure 6-8). Contrariwise, the spatial configuration of the other game setups allowed for more overlapped learning stages. For instance, the setup *'in front'* enabled pupils to shift from one learning stage to another while interacting in the same space (in front of *TouchTomb*), and then by associating their actions to the heritage context, they managed to reach the 'conceptualizing' stage of learning in an earlier phase of their interaction. Moreover, participants of *'inside'* game setup were compelled to enter the tomb from the beginning of their cycle of cultural learning, and thus the early contextualizing of the heritage artifact interwove their 'doing' and 'reflecting' learning stages. They were accordingly able to conceptualize their interaction by cognitively mapping the physical shape (i.e. human figures) and materiality (i.e. colors) of the artifact itself to the tokens (i.e. gender cards) of the *TouchTomb*. Unlike *'around'* setup, the heritage artifact was situated with a clear goal in the *'inside'* game setup from the early stage of pupils' learning process, resulting in the highest percentage of cultural learning as in Section 6.5.1 and illustrated in Figure 6-8.

Consequently, in tangible gamification endeavors for communicating heritage, we highly recommend situating heritage artifact in the early phases of visitors' interaction to allow for interwoven learning stages during their visit. In addition, spatial configuration of tangible gamification needs to be considered in how and when the physical context of heritage artifacts contributes to communicate the information, such as steering natural progression of learning by giving clues.

6.6.2. Cultural Learning as a Reward of Gamified Experiences

Embedding the intended knowledge to communicate in the reward system of gamified experiences supports informal cultural learning.

Our results show how the gradual rewarding system (i.e. progress bar) influenced the user experience and motivated participants to engage with the installation, gradually preparing for the grand, overarching reward (i.e. the revealed information). The need for intensive collaboration and problem-solving to solve the games, and the balance between the skills and challenge needed to achieve the intermediate goals, created a sense of anticipation for the overarching reward. This anticipation is observed in their rush to complete the tasks, as well as in the drive of the children in the groups of the '*inside'* game setup to collectively engage with the revealed information even when not directed by their teachers. Moreover, our results indicate successful transmission of the intended cultural learnings (as described in section 6.5.1). This feeling of anticipation and final learning outcomes is comparable to the relation previously established between learning and being in a state of 'flow' [Kiili, 2005]. Moreover in our case study there were indications of anticipation and learning even at a group level, in which the pupils divided to solve the various intermediate goals and then later re-joined for a collective reading of the revealed information (a reward 'given' to all simultaneously).

Accordingly, gamification techniques promise a great potential to enhance informal cultural learning by embedding the knowledge in a form of overarching rewards. Simple intermediate rewards, even of non-educational nature, can be utilized appropriately to retain motivation as well as to build-up anticipation for overall goals of cultural learning.

6.6.3. Sense of Ownership Causes Accountability

Creating a sense of ownership in tangible gamification motivates museum visitors by making them accountable for solving the game.

We noticed only in *'around'* game a few cases of exclusion, meaning that at least one participant was not involved among the group to solve the puzzle, while in *'in front'* game and *'inside'* game, all participants were involved in some way or form as they were compelled to place their cards. In *'in front'* game and *'inside' game*, cards were not unique, and they were distributed and given to all participants in hands. In contrast, puzzle pieces of *'around' game* were all placed on the table before pupils' participation, then they picked-up one by one to place them on the platform. Thus, this setup allowed for different kinds of aggressive behavior, such as we noticed several times (5, N=14) that one participant started to take puzzle pieces from others' hands as he/she knew where to place these pieces, to the extent that three children started to quarrel to have a certain piece of puzzle (Figure 6-11.a). Accordingly, a sense of ownership [Hornecker, 2004] was created among participants of *'in front'* and *'inside'* setups. By owning the physical cards, each of them felt accountable for achieving his/her own goal. Unlike the centered goal of *'around'* game setup on one artifact that became more challenging as no individual tasks were assigned, the game goals of *'in front'* and *'inside'* setups were distributed among pupils spatially and even temporally, so they coordinated and jointly determined the order of solving the game.

Consequently, we recommend that museum tangible gamification for young visitors should take into consideration the sense of ownership to make them more motivated and accountable for doing their assigned tasks, as each of their tasks was required to achieve the overall goal (i.e. cultural learning). This sense of ownership can be created when visitors receive physical tokens to interact with, or even by creating their own tokens. Sense of ownership might well be extended from merely tangible pieces or cards to the sense of sharing and owning the physical museum space when the setup of tangible gamification requires physical moving to multiple points of interaction.

6.6.4. Plurality and Diversification of Goals Fosters Collaboration

Collaboration among young museum visitors can be fostered in tangible gamification when it includes multiple and diverse goals distributed in space and time.

Using three game setups that can run simultaneously for three teams enabled us to engage all the classroom pupils on a group level, having separate goals to achieve. The setup of the game thus created a kind of competition among pupils (see Section 6.5.3). Though this competition was not intended in our design, since it emerged simply from calling the process a 'game' and sharing a progress bar. In effect, even though we documented competitive reasoning between teams, in each of the teams separately, we noticed collaboration practices that engaged all the individuals of each team since there were too many intermediate goals to be successfully achieved without coordination. Moreover, we observed that spatial diversification such as having to add the cards higher or lower to the ground allowed for different types of pupils in each team (e.g. of varying heights) to actively participate and collaborate in an inclusive way. The existence of multiple goals that were also spatially distributed, enabled all pupils to participate in the process, both individually and as a team thus making the 'game' an active element in their museum visit.

Tangible gamification in museums is orchestrated by embedding varying intermediate tasks that can be distributed in space and time. So, all visitors are engaged and can collaborate with each other depending on their features, interests, or assigned tasks. This orchestration should be designed based on the existing situation to determine the spatial and temporal distribution of tasks. For instance, visitors do not have to do everything all at once and overwhelm the infrastructure, thus physical clashing with each other can be avoided.

6.6.5. Playful Evaluation

Playful and collective questionnaires enable the evaluation of children's user experience in a short time and in loaded environments.

Our results showed how young museum visitors considered the tangible questionnaire playful and enjoyed answering it, as explained in Section 6.5.4.2. Associating the design of the questionnaire to their play experience (i.e. physical LEGO blocks) implicitly informed them what they must know and do in order to play and answer it [Salen and Zimmerman, 2004]. We argue that this kind of questionnaire differs from conventional and individual surveys in terms of (a) allowing and motivating pupils to collectively evaluate their experience in a very short time, and are thus possible in loaded environments, as shown in Figure 6-15.a, (b) using familiar gaming techniques to answer the questionnaire allows for playful and creativity aspects (Figure 6-15.b), (c) physically visualizing the answers allows for a potential comparison among the peers and thus reflecting on the different teams, and (d) similar to the game itself, distributing the physical tokens of the questionnaire (i.e. LEGO blocks) to participants creates a sense of ownership by making each of them more committed to answer all questions, as discussed in Section 6.6.3. On the other hand, this kind of questionnaire might create more biases in the results since participants are influencing each other not only passively by seeing the answers of other participants, but also actively by diverting each other to change their answers. Further, LEGO's are associated with a playful experience which can in this case hinder the need for more accurate or representative documentation.

Consequently, we recommend using playful and collective surveys in order to collect intense data from children and to evaluate their experience in loaded environments. Yet, these collective surveys might be biased since participants see each other's answers, but possibly truthful based on a shared understanding. Further studies are encouraged to ensure the validity of collective and playful questionnaires, and to investigate whether playful methods of evaluation could also stimulate children to report on other types of information (e.g. their cultural learning).

(a) (b)

Figure 6-15: *Qualities of the questionnaire: (a) participants are collectively answering the questionnaire in a loaded environment, and (b) a group of participants express their answers in a playful and creative manner.*

6.6.6. Shortcomings and Limitations

In our study, the experiments were deployed for a limited time in a real-life busy environment with a relatively large number of participants. Our participants were all young visitors (10-14 years old), who were relatively easy to motivate, yet hard to control and challenging to interview due to lack of focus and language barriers. At the same time, we believe that most of our findings can be generalized towards many other forms of tangible gamifications that are meant to communicate or educate heritage information towards young visitors.

Moreover, the intended cultural learning goals of our three game setups might not be equal in terms of easiness and interest, however we did not aim to compare the three setups out of viewpoint of effectiveness, rather to recognize intrinsic differences and their impact on learning and visitors' engagement. Due to the time limit, we were not able to ask our participants individually, we accordingly conducted the interviews in groups. In the group interviews, it was very challenging to ensure that all 5 pupils within a group have gained the same knowledge from their interaction, but we assumed that their collective answers might well contribute to the ultimate objective (i.e. cultural learning). Further, we did not notice a clear evidence that different teams learn from each other due to the limited time or the pressure of the unintended competition. However, further studies are encouraged to benefit from this 'missed' opportunity and to investigate whether the approach of tangible gamification causes an indirect learning among participants, for instance by transferring the knowledge from one game team member to a person in another team. Moreover, for a better assessment of cultural learning, we did design a post-interaction survey and sent it to certain teachers, who showed the interest and willingness to ask their pupils few questions about what they learned from their museum gamified experience in the following week. But unfortunately, none of them responded back to us. So, we relied only on the on-site interviews to evaluate the cultural learning of participants.

6.7. Conclusion

In this study, through a field study in a real-world museum environment, we presented *TouchTomb*, a tangible gamification installation that aims to communicate different types of tacit knowledge of an ancient Egyptian tomb-chapel in an informal cultural learning setup. We deployed a mixed-methods evaluation study to investigate how *TouchTomb* enhances the cultural learning of a total of 190 young museum visitors (pupils of 10 to 14 years old), and we examined the collaboration and engagement of visitors during their interaction flow that lasted for maximum 15 minutes, and how it affects the different stages of their cultural learning and enhances their museum visiting experience.

Our findings show several qualities of applying the approach of tangible gamification in museum context, such as enhancing informal cultural learning of young museum visitors by considering the physical context of heritage artifact in their interaction, and fostering engagement and collaboration among them by embedding varying intermediate tasks that can be distributed in space and time. We concluded the paper with a set of discussion points and design recommendations for future research or potential further development of tangible gamification that educate or communicate heritage in museums for young visitors, such as: situating heritage artifacts in cultural learning, including the learning in the reward system, engaging visitors by enabling them to own and to be accountable for their physical tokens, fostering collaboration among them by having a diversity of goals, and evaluating their experience in a playful and collective way.

Chapter 7: Conclusion

7

In this chapter, we discuss the five main contributions of this thesis: (a) an amended version of phygital heritage model as a potential medium of communicating heritage information, (b) a design workflow of phygital heritage, (c) four phygital prototypes, (d) six design guidelines, and (e) an evaluation framework for phygital heritage. We identify aspects of critical reflection and limitations of the work. We also highlight four directions for future work.

7.1. Amended Phygital Heritage Model

We proposed a model of phygital heritage (in Chapter 2) as a potential medium for more engaging and meaningful communication of heritage information. Based on our understanding and the overall results of this thesis, we present an amended version of Phygital Heritage model (Figure 7-1). In which, we made conceptual changes (highlighted in the model) such as: dissecting, inventing, adding, and shifting certain phygital approaches, as follows:

- *Dissecting* the phygital approach of AR technology into two approaches that are located differently in the model on the two axes: (a) 'see-through AR', which communicates information by superimposing virtual objects on the real scene via portable (e.g. smartphones and tablets [Vlahakis et al, 2002]) or wearable devices (e.g. HoloLens [Pollalis et al, 2017]), and (b) 'spatial AR', which augments the environment of visitors with images or videos that are projected directly on the physical reality [Raskar et al, 1998], it is more situated as the graphical depiction of information is directly and physically related to the artifact.
- *Inventing* and placing the phygital approach of 'tangible gamification', which was presented in *Neferirtenef Tomb-Chapel* (Chapter 6), between the two categories of integrated and actuated of the model. This approach combines tangible interaction with gamification, as a tangible interactive paradigm that encourages collaborative learning and physical interactivity of heritage visitors.
- *Adding* the phygital approach of 'tangible smart replicas' in the integrated phygital category, which resulted from the literature [Marshall et al, 2016]. This approach refers to embedding digital components into physical replicas of original heritage artifacts, aiming for an interactive experience (e.g. offering narrative content in addition to the traditional factual content).
- *Shifting* the approach of VR technology higher on the situatedness axis (i.e. vertical), based on our interpretation of situatedness and how it differs from context (see Section 7.4.4).

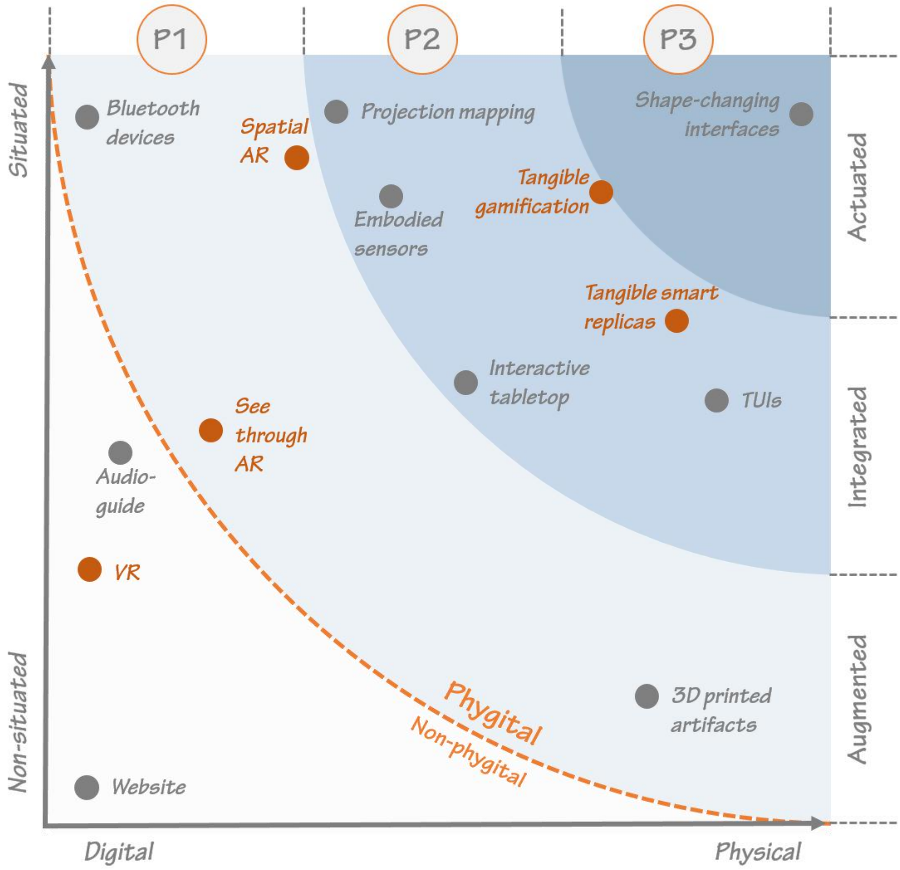


Figure 7-1: *An amended version of Phygital Heritage model (changes are highlighted), mapped along two characteristics: the physical affordance of information and the level of situatedness of how this information is communicated.*

7.2. Design Workflow of Phygital Heritage

The design process of our phygital prototypes typically followed four phases: (a) identifying the context, (b) deciding on the content, (c) prototyping, and (d) in-the-wild deployment. We believe that this design workflow (shown in Figure 7-2) will potentially help future designers of phygital heritage.

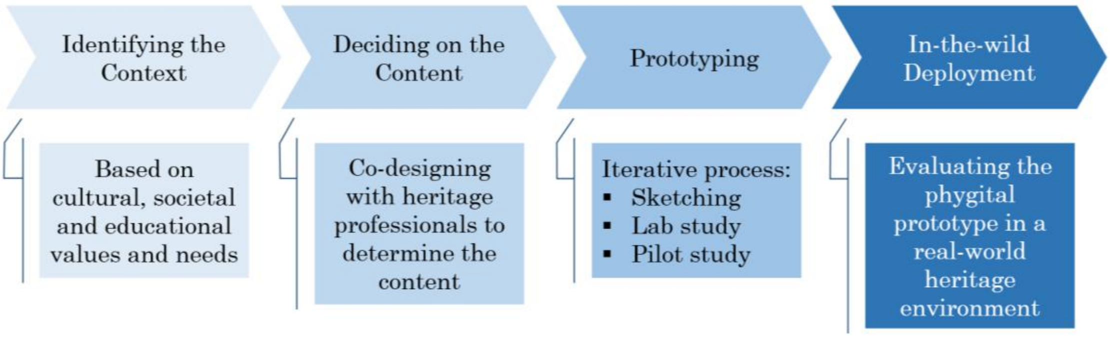


Figure 7-2: *A design workflow of phygital heritage: identifying the context, deciding on the content, prototyping, and in-the-wild deployment.*

7.2.1. Identifying the Context

The contexts of *Saqqara Entrance Colonnade*, *Nimrud Relief* and *Neferirtenef Tomb-Chapel* were a result of direct collaboration with the antiquity department of the Royal Museum of Art and History in Brussels. Museum curators proposed contexts of three masterpieces from the museum collection that have significant societal, historical and educational values. The museum possesses the largest collection of the Egyptian antiquities in Belgium. As such, the monumental scale model of Djoser pyramid complex in Saqqara could benefit from the empirical knowledge of our *Saqqara Entrance Colonnade* study to from a foundation of future exhibition designs. In addition, the original tomb of *Neferirtenef*, which is exhibited in scale 1:1 in a centric spot among the Egyptian collection at the museum is valorized in learning plans for school visits as part of their educational curriculum, and thus designing an informal cultural learning was an educational need. Further, the *Nimrud Relief* is considered one of the key masterpieces of the Near-Eastern collection in the museum. After the recent and deliberate destruction of the original palace in Iraq, exploring and finding methods to contextualize such an exceptional museum artifact became as an important mission.

On the other hand, the context of *Graethem Chapel* was chosen as a real heritage environment through a collaboration with the Culture Department of the municipality of Borgloon. The Chapel is a medieval heritage building that is listed as a historical monument since 1936, which is no longer used for worship, but instead functions as a gallery for art exhibitions. The Chapel is a prominent touristic attraction due to its rich archeological history and its architectural evolution that has been accurately dated. So, communicating the spatiotemporal transformation of the Chapel was a societal and touristic need.

7.2.2. Deciding on the Content

In our four studies, heritage professionals and museum curators were actively involved in deciding on the content (i.e. built heritage information) to communicate, and thus an appropriate phygital approach was followed, as formulated in Table 7-1. We deliberately followed the co-design approach to enable heritage experts to make creative contributions in the solution directions. The benefits of employing a co-design approach with experts include also improving knowledge of their needs, and generating better ideas with a high degree of originality and heritage values. In *Saqqara Entrance Colonnade* (Chapter 3), they proposed several contents, and together with them we deliberately chose the story that relates the physical and architectural characteristics of the entrance colonnade to a historical journey in ancient Egypt. We were motivated by the symbolic significance in this story to communicate it in tangible means using an interactive navigation and a passive representation. Accordingly, the comparison approach was followed to benchmark different tangible interaction and feedback modalities. In *Nimrud Relief* (Chapter 4), heritage professionals raised the issue of the recent destruction of the original palace of Nimrud, and accordingly they proposed a content that corresponds to their own problem statements, which is the architectural contextualization of the relief. We hypothesized that developing an AR experience to bring the digital content to the physical reality might be suited and therefore we combined it with a preceding conventional visit to benchmark the phygital qualities. In *Graethem Chapel* (Chapter 5), as a prominent touristic attraction due to its rich archeological history and its architectural evolution that evolved in several building phases over 850 years, together with heritage experts from academia and from the cultural sector, we chose the spatiotemporal transformation as a content to be communicated in-situ. Consequently, the interactive projection mapping was developed, combined with a TUI. In *Neferirtenef Tomb-Chapel* (Chapter 6), we conducted a co-design session with heritage professionals and museum curators, which resulted in choosing informal cultural learning on three types of tacit knowledge of Egyptian built heritage (e.g. architectural qualities, historical values and artistic features) to be communicated to school visits. Accordingly, the approach of tangible gamification was chosen that combined different game setups to enhance their informal cultural learning.

Table 7-1: *Matrix to map the types of heritage information (content) to the suitable phygital approaches.*

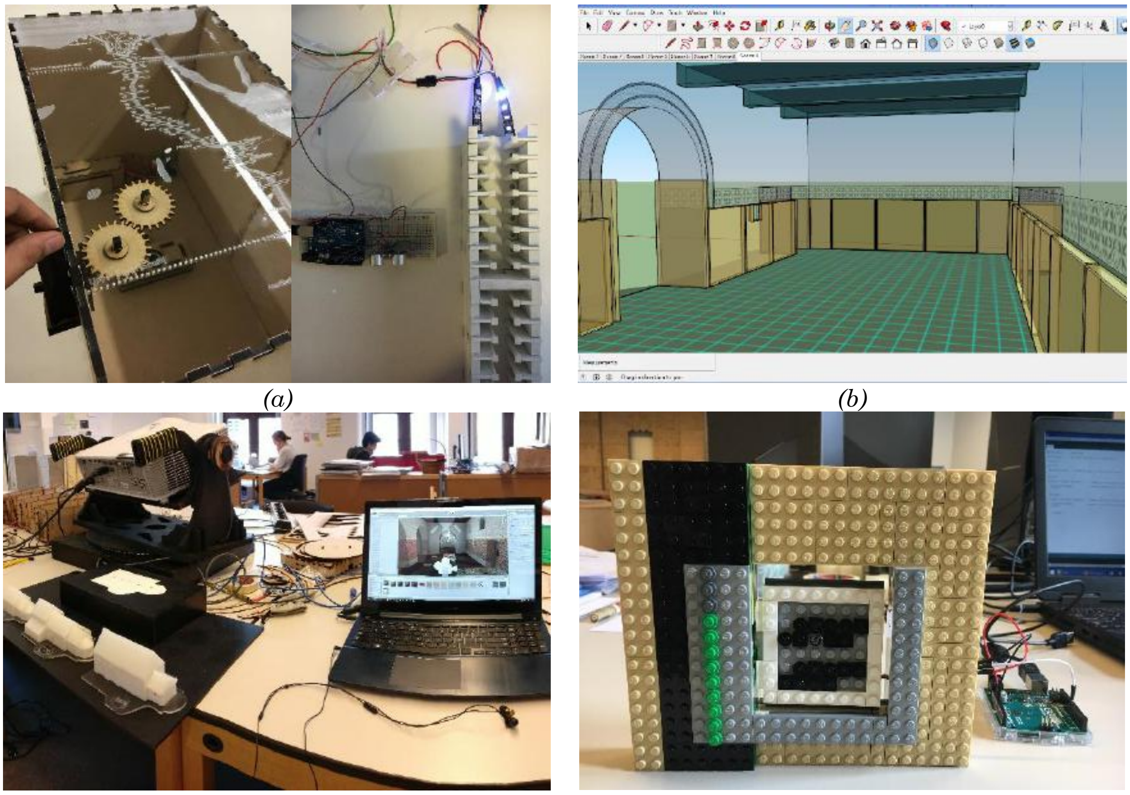
		Built Heritage Information								
		Architectural context	Spatial dimensions	Uncertain architectural features	Aesthetic features	Uncertain aesthetic features	Cultural meanings	Spatiotemporal transformation	Informal cultural learning	*More types of information →*
Phygital Approaches	**AR**	■	■	■						
	AR abstract visualization			▨						
	Freedom of user's movement	▨								
	TUIs		■				■	■		
	Grasping physical models		▨							
	Considering material characteristics						▨			
	Projection mapping				■	■		■		
	Interactive in-situ projection							▨		
	Semi-realistic representations					▨				
	Tangible gamification								■	
	Situating heritage artifacts								▨	
	Embedding varying intermediate tasks								▨	
	More types of phygital approaches →									

■ Suitable approach ▨ Consideration

In Table 7-1, we map the different types of heritage information (i.e. content) to the suitable phygital approaches that can be conveyed with (only the contents and approaches that were addressed in this thesis). Several design considerations are also mapped in the matrix based on our overall results. This 'in-progress' matrix can be further developed through future studies that investigate more phygital approaches for communicating different types of heritage information.

7.2.3. Prototyping

The design of interaction features was explored based on both the research question and the chosen heritage content. Each of the prototypes was then part of an iterative design process (Figure 7-3); after an initial sketching phase, a primary installation was prototyped and tested in the lab by invited volunteers (i.e., research associates not directly associated with the research) to interact with the prototype and give us insights about the required technical, methodical, and ergonomic alterations. Consequently, a working installation was tested in an ecologically valid context as a pilot study. Ultimately, the final phygital prototype was developed based on our observations and the remarks of users.



(a) *(b)*

(c) *(d)*

Figure 7-3: *Iterative design process of the four phygital prototypes: (a) experimenting several concepts for controlling the angle of view and illuminating the LED strip, (b) reconstructing the digital model of the original space where the artifact was located, (c) testing the installation in the lab before the pilot study, and (d) prototyping the rotation of the question plate using a Servo motor integrated in a LEGO installation as a proof of concept.*

7.2.4. In-the-Wild Deployment

Each prototype was evaluated in a real-world heritage environment such as a museum or a monument. Both the ethical permission and the museum permission were requested and obtained in advance. Locations for deployment were chosen in relation to the context of heritage artifacts and to the spatial requirements of the phygital prototypes: in the main showroom of the Egyptian collections in *Saqqara Entrance Colonnade*, two meters towards the original artifact in *Nimrud Relief*, in the center of the main nave of *Graethem Chapel*, and the replica wall installation of *Neferirtenef Tomb-Chapel* was located just outside the original artifact.

Participants were recruited (a) spontaneously in *Saqqara Entrance Colonnade* and *Nimrud Relief* by asking normal visitors of the museum to interact with the prototypes, (b) on invitation in *Graethem Chapel* via social media, posters in the city center, physical and electronic newsletters, and (c) by the museum public and educational service in *Neferirtenef Tomb-Chapel*, through contacting the scheduled school visits of the chosen age category to the Egyptian collection.

7.3. Phygital Prototypes

In this thesis, we presented four phygital prototypes that communicated different forms of built heritage information in several contexts. These prototypes benefited from emerging technologies and phygital approaches, and they were created with rapid fabrication in FabLab using materials such as MDF wood and 3D printing polymers. All of the prototypes were deployed in real-world heritage environments to reach different types of visitors. Table 7-2 shows a comparison among the four phygital prototypes in terms of the built heritage information to be conveyed, the approach and design of the interaction, and the overall experimental study.

Table 7-2: *Comparison of the different characteristics of the four phygital prototypes.*

		Saqqara Entrance Colonnade	***Nimrud Relief***	***Graethem Chapel***	***Neferirtenef Tomb-Chapel***
Objective		To introduce a potential medium for more enriched and playful communication of heritage values and qualities.			
Contribution		Heritage communication - User engagement - Evaluation of experience			
Built Heritage	Scope of heritage information	Ancient Egyptian	Assyrian	Medieval	Ancient Egyptian
	Type of tacit knowledge	Symbolic significance	Architectural contextualization	Spatiotemporal transformation	Informal cultural learning
	Heritage environment	Museum	Museum	Monument	Museum
	Contextualization	Non-contextualized	Non-contextualized	Contextualized	Contextualized
Phygital Interaction	Approach	Comparison	Interactive visit	Interactive visit	Gamification
	Technology	TUI	AR	TUI + PM	TUI
	Input medium	Touch screen (C1) - Tangible installation (C2, C3)	Tablet's camera	Physical model	Tangible installation
	Output medium	LCD display (C1, C2) Physical model (C3)	Tablet's screen	Projection	Physical/digital progress bar + physical plates of textual information
	TUI Material	Wood + 3D printing polymer	/	Wood + 3D printing polymer	Wood + 3D printing polymer
	Input scale	Scale model	Real scale (part)	Scale model	Real scale
	Output scale	Scale model	Real scale	Real scale	Real scale
	Situatedness	Non-situated	Slightly situated	Situated	Fully situated
	Social interaction	Interface allows	Interface does not encourage	Interface highly encourages	Interface requires
Study	Participants	42	26	14	14
	Total number of visitors	86	46	28	190
	Pilot study	2 days	2 days	1 day	/
	Deployment time	2 weeks	2 weeks	1 week	4 weeks

It is worth mentioning that during the course of my PhD research, I actively participated in conceptualizing, designing and creating six more phygital prototypes, which are explained in Appendix II. In which, I report on my participation in various training programs and international workshops, such as museum camps and summer schools.

7.4. Design Guidelines

We discuss the implications of the overall results of the thesis with relevance to future research and potential further developments of alternative approaches to communicate the meanings and values of heritage. We outline several design guidelines that support heritage communication through phygital mediums to public visitors. These guidelines are based on the design recommendations formulated in the different chapters (Chapter 3 to Chapter 6). The guidelines provide an answer to the main research question and the sub-research questions of the thesis, as illustrated in Table 7-3:

- ***RQ0.* How can *"phygital heritage"*, the integration of digital technology into physical reality, facilitate the communication of built heritage information to museum visitors?**

- *RQ1 Communication.* How can phygital experience enhance the communication of built heritage information?
- *RQ2 Engagement.* How can phygital experience influence visitors' engagement and foster social interaction in museums and heritage environments?
- *RQ3 Situatedness.* How does the level of situatedness influence the phygital experience of communicating heritage information?
- *RQ4 Physical affordance.* How does the level of physical affordance influence the phygital experience of communicating heritage information?
- *RQ5 Evaluation.* How can phygital heritage be evaluated in heritage environments such as museums?

Table 7-3: *Overview of the design recommendations of the different Chapters with the relation to the research questions.*

Ch.	Design Recommendations	Research Questions				
		1	2	3	4	5
Ch. 3. Saqqara Entrance Colonnade	*3.a.* • An equilibrium needs to be sought between the physical affordance and required cognitive effort when combining tangible interaction navigation and representation modalities (RQ1, RQ2, RQ4).	✓	✓		✓	
	3.b. • Enabling heritage visitors to grasp physical models and to bring them to their eye-level facilitates the communication of correct scale and more detailed information (RQ1, RQ4).	✓			✓	
	3.c. • Tangible interaction requires considering the material characteristics such as embodiment, physical abstraction, and materiality for enabling heritage visitors to acquire the cultural meanings (RQ1, RQ4).	✓			✓	
	3.d. • An equilibrium needs to be found between the positive qualities of tangible interaction via physical representations and the actual level of realism that can be fabricated (RQ4).				✓	
	3.e. • Chronological mapping of user's focus of attention when combining multiple tangible interaction modalities for navigation and representation (RQ5).					✓

Ch.	Design Recommendations	Research Questions				
		1	2	3	4	5
Ch. 4. Nimrud Relief	*4.a.* • AR could become an effective medium to convey the architectural features and spatial dimensions of museum artifacts and their related contexts (RQ1).	✓				
	4.b. • Levels of embellishment in AR visualization should be mapped to the user's focus of attention for the intended communication (RQ1).	✓				
	4.c. • AR abstract visualization might be suited for communicating uncertain heritage information, considering aspects of transparency and choice of colors (RQ1).	✓				
	4.d. • AR museum experience should stimulate different forms of curiosity about the architectural, historical or social contexts (RQ1, RQ2, RQ3).	✓	✓	✓		
	4.e. • Freedom of movement during the AR experience causes a better communication of architectural context of artifacts (RQ1, RQ2, RQ3).	✓	✓	✓		
	4.f. • AR experiences in museums should consider including some kind of instructions to overcome the usability issues (RQ2).		✓			
	4.g. • AR museum experience should take into consideration the age-related differences, such as less complex interfaces and larger screens (RQ2).		✓			
	4.h. • Logging the user's angle of view to evaluate the usability and intuition of AR experiences in museums (RQ2, RQ5).		✓			✓
	4.i. • Sketching is a novel evaluation method to capture the participants' perception and memorability of contextual information such as architectural features (RQ5).					✓
Ch. 5. Graethem Chapel	*5.a.* • Not only one interaction modality is ideal for all the required tasks in heritage communication (RQ1).	✓				
	5.b. • An equilibrium needs to be sought between the educational and entertaining role of the installations that meant to convey heritage information to lay visitors (RQ1, RQ2).	✓	✓			
	5.c. • In-situ interactive projection mapping could become an effective medium to communicate the aesthetic features of architectural heritage (RQ1, RQ3).	✓		✓		
	5.d. • Uncertainty of aesthetic features should be visualized in semi-realistic representations in order not to break the immersion (RQ1).	✓				
	5.e. • TUIs can be a combined with projection mapping to communicate the spatiotemporal transformation of architectural heritage (RQ1, RQ4).	✓			✓	
	5.f. • When technology is too novel to public, installations should be self-explanatory, easy to learn and provide affordance for how to use in public context (RQ2).		✓			
	5.g. • Designing an experience that can be shared and physically explored by multiple visitors encourages social interaction (RQ2, RQ4).		✓		✓	
	5.h. • Physical models should be robust enough, having a durable look to stimulate visitors to touch and examine them from inside and outside (RQ2, RQ4).		✓		✓	
	5.i. • Chronological mapping of user's interaction when combining more than one modality to communicate heritage (RQ5).					✓
Ch. 6. Neferirtenef Tomb-Chapel	*6.a.* • Situating heritage artifacts in the early phases of visitors' interaction, allow for more interwoven learning stages in their visit (RQ1, RQ3).	✓		✓		
	6.b. • Gamification techniques enhances informal cultural learning when the information is included in the reward system (RQ1, RQ2).	✓	✓			
	6.c. • Tangible gamification in museums can be orchestrated by embedding varying intermediate tasks distributed in space and time (RQ2).		✓			
	6.d. • Creating a sense of ownership for museum visitors in tangible installations motivates them and makes them accountable for doing their assigned tasks (RQ2, RQ4).		✓		✓	
	6.f. • Mapping user's spatial interactivity with the relation to heritage artifacts to assess the interwoven learning stages (RQ3, RQ5).			✓		✓
	6.g. • Novel evaluation method to collect intense data from children playfully and collectively in loaded environments (RQ5).					✓

7.4.1. The Design of a Phygital Experience Should Be Driven by the Heritage Content

> This Guideline responds to the research question (RQ1) and it is based on design recommendations: 3.b, 3.c, 4.a, 4.b, 4.c, 4.e, 5.c, 5.d, 5.e, and 6.b (see Table 7-3).

In heritage communication, the choice of the phygital approach is driven by the heritage content. In each of our four studies, we explained (in Section 7.2.2) how we started first with defining the heritage content, which steered the entire process of deciding on the technology, adopting the approach and conducting the evaluation study.

Consequently, we recommend that designing a phygital museum experience should not be initiated by the technology. Instead, heritage content has to be the foundation of deciding on the phygital approach to be utilized in communication. For instance, for communicating spatial dimensions, approaches towards physical are more recommended (see the model of phygital heritage in Figure 7-1), while digital approaches are more appropriate for communicating the aesthetic features. Real scale approaches are suggested when the content is related to the architectural context, in which visitors are also encouraged to move around. Likewise, tangible gamification approaches might be suited to enhance informal cultural learning by including varying entertaining tasks. Moreover, narrative contents require approaches towards high degree of situatedness, and combining multiple approaches benefits the interlinked contents that needs to be shared among visitors. Yet, the matrix illustrated in Table 7-1 needs to be extended and developed by further studies that investigate more phygital approaches (Figure 7-1) for communicating the different forms of heritage information to help designers and museum curators for picking out the appropriate phygital approaches based on the intended heritage content to be communicated.

7.4.2. The Design of a Phygital Experience Should Aim to Bring Visitors Together

> This Guideline responds to the research question (RQ2) and it is based on design recommendations: 4.g, 5.g, and 6.c (see Table 7-3).

Phygital heritage allows for interactive prototypes to be experienced by multiple visitors, who engage and collaborate with each other depending on their interests or assigned tasks. It is widely admitted that establishing social relationships during informal learning processes is among the main expectations of museum visitors [Vermeeren et al, 2018]. Our results on engagement and social interaction in *Graethem Chapel* (Chapter 5) and *Neferirtenef Tomb-Chapel* (Chapter 6) showed how the phygital experience can be socially shared and orchestrated among visitors by embedding varying intermediate tasks that can be distributed in space and time. The orchestration of the experience should be designed based on the existing affordances in the situation to determine the spatial and temporal distribution of tasks. For instance, visitors do not have to do everything all at once, but instead they are encouraged to take on different roles of interaction (e.g. leader, follower, interpreter, etc.), and to switch roles among themselves. Consequently, we recommend the design of phygital experience to be socially shared and physically explored by multiple visitors.

7.4.3. Phygital Heritage Should Be Self-Explanatory and Avoid Overwhelming

> This Guideline responds to the research question (RQ2) and it is based on design recommendations: 3.a, 4.d, 4.e, 4.f, 5.f, 5.b, and 6.c (see Table 7-3).

Phygital heritage prototypes have the risk to overwhelm visitors. Our pilot studies revealed several usability issues that we considered later on in the large scale studies. Most of these issues were related to overwhelming visitors and how the prototypes were not so intuitively understandable to visitors. During the different studies in this thesis, we presented different strategies in order not to overwhelm visitors when they engage with phygital heritage. For instance, the required cognitive effort should be balanced with the affordance of the interface (i.e. in Chapter 3 – *Saqqara Entrance Colonnade*). Further, the phygital experience can be shared among visitors by playing different roles (i.e. in Chapter 5 – *Graethem Chapel*), or it can be orchestrated among visitors by embedding varying intermediate tasks that can be distributed in space and time (i.e. in Chapter 6 – *Neferirtenef Tomb-Chapel*). Yet, these strategies are not exhaustive, but they have shown how phygital experience should be designed as self-explanatory and easy to learn in order not to overwhelm and distract. Phygital experience should also provoke the curiosity of heritage visitors to interact and to share the experience among them.

7.4.4. The Design of a Phygital Experience Should Consider the Situatedness of Heritage Artifacts

> This Guideline responds to the research question (RQ3) and it is based on design recommendations: 4.d, 4.e, 5.c, 6.a, and 6.e (see Table 7-3).

Situating heritage artifacts in the phygital experience influences the communication of information and engagement. The terms of situation and context are often used synonymously. However, to derive situatedness from the interaction of situation and context it is necessary to dissociate these connotations. Situatedness refers to specific situations in which actions take place [Rohlfing et al, 2003], where actions are understood not only as task-oriented behavior but in a broader sense. In contrast, context is a general construct that depends on various local and global factors.

In *Saqqara Entrance Colonnade* (Chapter 3), although heritage artifact was not contextualized in the experience, visitors were situated to some extent in the experience as they were in the main showroom of the Egyptian collections in a real world museum environment, receiving information about an Egyptian monument. Likewise, in *Nimrud Relief* (Chapter 4), the AR experience architecturally contextualized the artifact in an attempt to situate museum visitors virtually in the original palace. The phygital experience was more situated in *Graethem Chapel* (Chapter 5), where visitors were already located in the heritage environment, learning about the history of the Chapel in an immersive experience. The level of situatedness was even well-addressed in *Neferirtenef Tomb-Chapel* (Chapter 6) by designing three game setups, which distributed the learning cycle of visitors in terms of how they occurred in space and time in significantly different ways.

Mapping these levels of situatedness to the different layers of communicating heritage information, we found that situating heritage artifacts in real-scale during visitors' experience influenced the comprehension of the architectural features (e.g. spatial dimensions). For instance, we had overestimations of dimensions in *Saqqara Entrance Colonnade* (particularly with the conditions of digital representations), compared to the real-scale visualization of *Nimrud Relief* and *Graethem Chapel* that enabled visitors to correctly estimate dimensions and other architectural features. Moreover, the high level situatedness of *Neferirtenef Tomb-Chapel* positively affected the cultural learning. In general, we recommend considering the level of situatedness in designing phygital experiences for communicating heritage information, particularly for communicating architectural features. Our results showed how situating heritage artifact in the early phases of visitors' experience, allowed for interwoven learning stages.

7.4.5. The Design of a Phygital Experience Should Exploit the Physicality of Heritage

> This Guideline responds to the research question (RQ4) and it is based on design recommendations: 3.a, 3.b, 3.c, 3.d, 5.e, 5.g, 5.h, and 6.d (see Table 7-3).

Exploiting the physical qualities of heritage artifacts, such as material-driven affordances (e.g. size, shape, texture, color, weight, etc.), touch and manipulation affordances, and grasping physical models (e.g. replicas of original artifacts), lead to intuitive and memorable forms of communication. Evidence from educational psychology shows that the manipulation of physical representations of information facilitates understanding [Jansen et al, 2015].

Consequently, we recommend that the phygital experience should exploit the physicality of heritage artifacts and to empower visitors to discover and decipher their meaning, such as (a) enabling visitors to grasp the physical scale models of heritage buildings for conveying spatial information, (b) giving physical tokens to heritage visitors to create a sense of ownership among them, which motivates them to do their assigned tasks, or (c) considering the material characteristics (e.g. embodiment, physical abstraction, and materiality) as powerful design aspects in steering useful forms of phygital heritage. Yet, objects of phygital heritage require affordable and robust forms of technology, which cannot be simply stolen or damaged, and thus issues of cost and ease of replacement should be well considered.

7.4.6. Phygital Heritage Should Consider the Combination of Different Modalities

> This Guideline responds to the research questions (RQ1, RQ2 and RQ4) and it is based on design recommendations: 3.a, 5.a, 5.e, and 5.g (see Table 7-3).

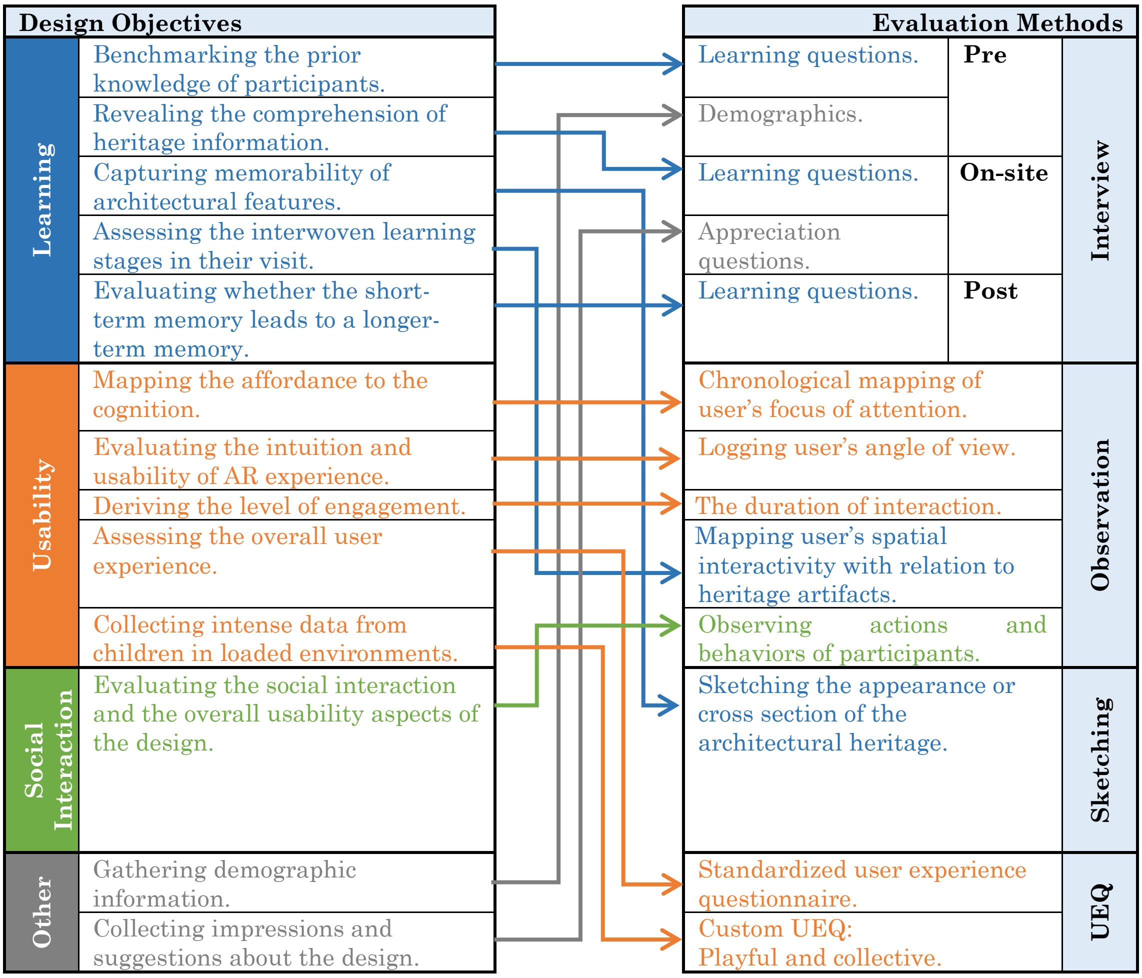
The seamless combination of different modalities from the phygital model enables heritage visitors to perform simultaneous actions. In *Saqqara Entrance Colonnade* (Chapter 3), the combination of several modalities allowed heritage visitors to construct a meaningful link between an interactive navigation and a dynamic representation. Likewise, in *Graethem Chapel* (Chapter 5), the two modalities stimulated visitors to explore more and to confirm their comprehension of architectural heritage. Consequently, we present two considerations of combining more than one modality for communicating heritage information to lay visitors: (a) only a single modality should require the conscious discovery of new affordances from visitors, or require much and continuous cognitive effort to be operated, and (b) the choice of the modalities should depend on the specific focus or narrative of the intended communication, as explained in Section 7.4.1.

7.5. Evaluation Framework of Phygital Heritage

This Framework responds to the research question (RQ5) and it is based on design recommendations: 3.e, 4.h, 4.i, 5.i, 6.f, and 6.g (see Table 7-3).

We deployed a mixed-methods evaluation methodology in our phygital heritage studies to assess the communication of heritage information and user engagement. Methods such as observations, interviews, and questionnaires are commonly used in the field of HCI to evaluate usability and functionality of interactive systems [Wania et al, 2006]. However, phygital heritage has broader aspects that needed to be covered in the evaluation process, such as learning, usability, and social interaction among heritage visitors. Therefore, we presented novel evaluation methodologies such as sketching, mapping the visitors' focus of attention, logging their angle of view, playful questionnaire, and pre and post interviews. In Table 7-4, we present an evaluation framework of phygital heritage communication, indicating when and how to use the different methods based on the design objectives.

Table 7-4: Framework for the evaluation methodology of phygital heritage communication.



For instance, inviting visitors to sketch the architectural heritage to captures their learning and memorability of architectural features (e.g. spatial dimensions). Likewise, the use of pre and post interviews benchmarks the prior knowledge of visitors and evaluates their memorability of heritage information. Moreover, for evaluating the usability aspects such as mapping affordance to cognition, visitors' focus of attention needs to be observed and mapped, while logging their angles of views evaluates the intuition of interface. In addition, we custom-designed a playful and collective user experience questionnaire to collect data from children in loaded environments. In general, we consider this framework as a guideline for future research of communicating built heritage information through phygital mediums to general visitors.

7.6. Critical Reflection and Limitations

We are aware of the fact that when we use the term 'built heritage' in this thesis, we make a simplification of it. Built heritage is quite a broad term, encompassing a vast amount of values. Built heritage refers to the study of human activity not only through the recovery of tangible (e.g. form and design, materials and substance, location and setting), but also through intangible (e.g. use and function, traditions and techniques, spirit and feeling) aspects [Van Balen, 2008]. Values of built heritage include – but are not limited to – [D.A.H.G., 2011]: (a) *architectural values*, such as the work of a known or distinguished architect, or the design or decoration of a particular interior space; (b) *historical values*, such as the location of an important event, an associated historic figure, the original use of materials, or the rarity of a building; (c) *artistic values*, which include examples of particular craftsmanship, decoratively carved statuaries or sculptures; (d) *cultural values*, which refer to works of the past that have acquired cultural significance with the passing of time; (e) *social values*, which embrace qualities for which a building has become a focus of spiritual, political, symbolic or other sentiment to a society; and (f) *structural values*, which relate to engineering or structural aspects such as innovative construction techniques. These categories of values are not mutually exclusive. For example, a certain case of built heritage may be of historical as well as architectural values.

In this thesis, we only covered the communication of certain types of heritage information (more specifically architectural meanings and values) that were relevant for each of the case studies. However, our phygital prototypes did not cover other heritage values that were not immediately related to each of those cases. For instance, in *Nimrud Relief*, we only evaluated the transfer of heritage-related knowledge in terms of the architectural context of the palace; however, museum visitors might have been more interested in the historical values of the palace, its societal role, or the spirit and feelings of the palace in the past. At the same time, our installation might have communicated additional heritage values alongside for which we did not design for. Likewise, the pupils in *Neferirtenef Tomb-Chapel* learned only simplified pieces of information about Egyptian heritage, while Egyptian antiquities that people are fascinated by around the world are much more impressive and richer, insofar that it still forms the foundation of a vibrant field of study on its own: 'Egyptology'. It could be a hypothesis – that we have not investigated – that once pupils understood hieroglyphs during our game, they might have positive feelings and be excited about Egypt. Perhaps this might start some interests in heritage in a general sense. In other words, this limitation in terms of design goals and evaluation focus implies that visitors' appreciation and engagement might influence more or other values than those that were conveyed to them. Therefore, for a more comprehensive approach, a technique of value assessment (e.g. Nara grid [Van Balen, 2008]) might be well applied by heritage professionals to valorize the use of phygital prototypes by encompassing the most relevant values and information of built heritage, which can be done during the content phase in our design workflow of phygital heritage.

Moreover, the work presented in this thesis (focusing on phygital heritage) is limited to a more digital – and perhaps ICT – technology driven domain of heritage. Yet the term 'digital heritage' is generally used to describe the utilization of digital technologies in the service of interpretation, conservation or preservation of heritage [Roussou, 2002]. It typically includes three major sub-domains [Addison, 2001; Tan and Rahman, 2009]: (a) *documentation*, which is about finding information, analysis and documenting the authentic data from both cultural and architectural past; (b) *representation*, which is conditioned by media and mostly focused on accuracy of visualization; and (c) *dissemination*, which is devoted to distributing information and knowledge to general public by means of interactive digital media, including those distributed and deployed in-situ, via the internet or via independent physical installations. These sub-domains are highly correlated, as heritage cannot be visualized without an accurate documentation of the relevant authentic data. In general, communicating heritage information to the general public cannot occur without first having represented and visualized the collected information, i.e. via the documentation and the representation phases. Therefore, our work belongs to the last sub-domain, i.e. disseminating and communicating heritage information that was already documented and represented in terms of digital heritage. For instance, in *Saqqara Entrance Colonnade* and *Graethem Chapel,* our research relied on pre-existing online digital models of built heritage; while in *Nimrud Relief*, we contributed also to the representation domain as we digitally reconstructed the model ourselves based on already available historical information. In some cases, stakeholders might need to combine the three sub-domains of digital heritage in order to pass on information to future generations, and to raise community awareness about heritage meanings and values.

We are aware that heritage communication should not be only about remembering certain information, for a certain period of time. Although we deployed a mixed and rich evaluation methodology in our four studies to evaluate the communication of heritage information, most of our evaluation methods were deployed only in-situ assessing how visitors could directly recall heritage information after the experiment, and sometimes asking them in groups, meaning that it was challenging to ensure that all visitors (i.e. participants) have gained the same knowledge from their interaction, and for how long they will remember it. Nevertheless, we recommend further investigations to evaluate whether this short-term memory might well lead to longer-term memory, in order to valorize the approach of 'phygital heritage', and to set it in the society of today.

In the context of our research, the internal validity refers to how well our experiments were done, and to which extent they established a trustworthy and meaningful relationship between the cause (i.e. our approach) and the effect (i.e. our findings). We realize that the subjectivity of the corresponding researcher influenced the internal validity, as this subjectivity was intimately involved in the overall research due to the applied qualitative methodology, meaning that how his judgment, observation and interpretations might have been shaped by personal opinions and emotions. Despite of that, we considered several aspects to improve the internal validity, such as: (a) conducting a pilot study before the large-scale study in order to reveal any obvious usability or other user experiential issues within an ecologically valid context; (b) the randomization of participants in the first three studies by conducting the experiments at different times to reach varying types of museum visitors; (c) having a control group in *Nimrud Relief* by inviting participants to conventionally visit the artifact and interviewing them before they interact with the phygital prototype; (d) deploying mixed-methods of evaluation to measure and assess the different design objectives; and (e) triangulation of researchers in *Nimrud Relief*, *Graethem Chapel* and *Neferirtenef Tomb-Chapel*, who interviewed participants to avoid possible personal bias, they also partially contributed to the analysis.

Nevertheless, the subjectivity of the corresponding researcher might have affected not only observing and interviewing participants, but also the analysis and the interpretation of results. We believe that reducing a researcher's biases, prejudices and assumptions is required to improve the internal validity [Norris, 1997], but at the same time the subjectivity cannot and should not be completely avoided. Instead, qualitative research should embrace subjectivity and seeks to understand why it occurs. For instance, being the designer and the maker and at the same time the evaluator of the prototypes might have created a sort of bias, but this is the way how design-oriented research is conducted. The bias might have been also emerged due to being an Egyptian intending to communicate Egyptian heritage to western visitors in a royal museum in Belgium. So, the cultural and religious background could have created a sensitivity towards interviewing people, particularly when the issue of destroying Nimrud palace by ISIS is raised in *Nimrud Relief*. Further, conducting interviews in English might have influenced the results, as some participants might have preferred to express themselves in their own languages. Admittedly, becoming a father in a growing family and enjoying to teach and to play with children, probably became a personal motivation to conduct the last study (i.e. *Neferirtenef Tomb-Chapel*). In general, I am aware that I am a person with a particular value system and specific qualities that could have influenced the interviews or the analysis process, such as my communicative character or my analytical skills. Likewise, I am aware also that I have been influenced by the many ideations and the kinds of research in our research group, such as its focus on design creativity and physical computing. This influence might have shown how the technological capabilities were getting more and more sophisticated through the four studies, and how the participation goal was getting more and more specific.

Concerning the generalization of the conclusion, we are aware that our results are contextually linked to the determinants of each of the studies. Thus, generalizing the results require taking into considerations several criteria by expanding the scope of the study. We tried to generalize the findings of each study, and then synthesize all the findings in guidelines. We also attempted to take obvious generalization issues into account, such as by diversifying the participant cohort (i.e. visitors with different ages and backgrounds, and with varying degrees of expertise). But at the same time, this research is based on “in-the-wild” research [Chamberlain et al, 2012], which implies that we were confronted with a wide range of contextual factors that might have colored our results and conclusions. For instance, the city of Brussels witnessed a terrorist attack in the middle of the study presented in *Saqqara Entrance Colonnade* (22 March 2016), which caused a closure of the museum on that day and a delay in our experiment. The practical consequences of that terrorist attack extended for long time, such as the intense security screening, the caution of people to exist in public spaces, and thus the decreasing number of visitors at the museum. Many people tended to avoid talking to foreigners, so those who participated in our study might not be fully representative to the population. Moreover, the complicated administrative system at the Royal Museum of Art and History forced us to obtain a permission not only from the Antiquity Department, but also from higher levels of management. Setting up the installations required a coordination with several services at the museum, such as the public service, the educational service, and the central dispatch. In some cases, we needed to plan everything long time in advance to cope with these complexities. In addition, language barriers might have influenced our results, as all interviews were conducted in English although some visitors preferred to express themselves in their mother language (i.e. French or Dutch). In general, visitors vary in their ways of answering interview questions from quiet and taciturn persons who barely answer questions with minimal information to more communicative and outspoken persons who like to tell more stories and convey more information about their personal experiences and values. Not all visitors were genuinely motivated to participate in our studies. For instance, all pupils in *Neferirtenef Tomb-Chapel* were obliged to participate in our study as part of their school-visit to the museum, but they were notwithstanding enthusiastic to do so. Moreover, we noticed that the weather conditions played a role in when and how people visited the museum, as when it is a sunny day (i.e. nice weather) people prefer to go outside in outdoor spaces, causing a decline in the number of museum visitors. Lastly, we were influenced by the behavior of visitors, as we faced a situation of a vandalism that happened during the study presented in *Neferirtenef Tomb-Chapel*, when an unaccompanied child misbehaved and damaged several motors in the installation. This led to postponing the experiment and taking more precautions by covering and securing the installation.

In general, we did try to react to such contextual situations to the best of our capabilities. So that, obvious aspects of robustness, safety issues, ergonomics, and language barriers were already considered in our designs, and thus our guidelines are specifically formulated to designers and researchers. To sum up, based on these critical reflections, we still stand behind the findings. Yet, we recommend that readers should take all of these contextual factors into consideration.

7.7. Future Work

The features of “inclusive”, “educational” and “participatory” of heritage museums are recently highlighted to democratize culture by integrating individuals in the public domain. These features have transformed heritage museums into institutions, in which the design of visitors’ interaction with heritage artifacts is shaped by their requirements and needs [Karayilanoğlu and Arabacioglu, 2016]. Here we highlight future directions and emerging research questions based on our results.

7.7.1. Designing for an ‘Inclusive’ Museum

Phygital heritage can be designed to attract new target audience (i.e. category of visitors) by accommodating their needs and requirements. Motivated by the concept of ‘inclusive museum’ [Karayilanoğlu and Arabacioglu, 2016] that embraces all parts of the society and empowers museum visitors to develop it, we believe that the approach of phygital heritage promises several opportunities to address other specific visitorships based on their age (e.g. children), vision (e.g. blind and visually impaired persons), mobility (e.g. handicaps), or socio-cultural aspects (e.g. immigrants and refugees). Including the needs and requirements of these heterogeneous visitorships in the phygital approaches is recommended for future investigations. For instance, the tangible gamification approach facilitates the learning of a group of children in an engaging and collaborative experience *(Neferirtenef Tomb-Chapel)*. Likewise, the tactile exploration might well enable blind and visually impaired persons to interact with heritage collections by touching specific hotspots on artifacts. Further, phygital heritage has the potential to enhance not only the accessibility of museum space [Vermeersch et al, 2018], but also the accessibility of exhibits per se for handicaps. Enabling visitors to map information into multimodal ways of human perception might well facilitates promoting intercultural skills for the social inclusion.

7.7.2. Designing for the Arab World

The context of in-the-wild studies influences the design, deployment and evaluation of interactive systems. Each two contexts are not the same; not within one country, nor one city or even one neighborhood. In general, there is a gap between HCI research in the Arab region and the West due to socio-economic and political contextual factors [Alabdulqader et al, 2017]. We believe that deploying the approach of phygital heritage in another cultural context such as the Arab region will look like differently. Here, by the term ‘context’, we denote the sets of circumstances that are involved in the HCI evaluation process. We categorize the contextual factors that might well influence phygital heritage into the following categories, on which we reported in our position paper (see Appendix I) in the Workshop “Designing for the Arab World” as a part of Designing Interactive Systems Conference (DIS ’17) [Nofal et al, 2017.b]:

- *User characteristics:* habitual patterns of behavior, personality and emotion (e.g. ability to work, time-value, patience, etc.).
- *Socio-cultural factors:* lifestyle measurements of both financial viability and social standing (e.g. education, religion, income, etc.).

- *Built environment features:* places and spaces that created or modified by people (e.g. the aesthetics of buildings, public spaces, transportation systems, etc.).

Therefore, we argue that phygital heritage promises several qualities in the Arab world to communicate the vast amounts of heritage information to public visitors. The future of phygital heritage in this region includes raising community awareness about heritage assets, and empowering citizens to appreciate their own heritage in more experiential ways. Yet, future studies should investigate the influence of the aforementioned contextual factors on phygital heritage in this region. For instance, phygital installations should be designed to support groups of interactions, as Arabs tend to interact as committed members of a group, rather than an independent individuals [Barakat, 1993]. With regard to the evaluation process, video recordings might not be suited in observation, as women are not eager to be photographed in public [Abokhodair and Vieweg, 2016]. Further, behavioral evaluation methods such as eye-tracking and observations should be adopted, as Arabs tend to express themselves spontaneously and freely in several situations, particularly in those related to human emotions [Barakat, 1993].

7.7.3. Designing 'with' instead 'for' Visitors

As we stated previously that heritage professionals and museum curators were involved in the design process of our prototypes. Yet, more research is needed to investigate methodologies for pluralizing approaches of phygital heritage by involving not only heritage professionals, but also heritage visitors (i.e. end-users) not as passive audiences but as active users, co-designers and co-creators [Vermeeren et al, 2018]. Like all design techniques, participation is a strategy that addresses specific problems. Participatory strategies are believed to be practical ways to enhance, not replace, traditional cultural institutions [Simon, 2010]. By providing visitors with an opportunity to share their creative, critical and reflexive input, participatory design studies are expected to cultivate responsibility and ownership among the broader public to raise the level of cultural democracy. Since phygital porotypes are created with rapid fabrication in FabLabs, so involving visitors in designing their phygital prototypes would correspond to the ambitions of digital fabrication movements by enabling students' education and citizens' empowerment. For instance, students might come across several concepts in science and engineering during their phygital prototyping in a meaningful, contextualized and engaging ways [Blikstein, 2013]. Abstract ideas such as friction and density become meaningful when they are needed to accomplish a task within a project, math thus becomes a necessity in a heritage project. Moreover, involving visitors in designing the phygital prototypes might well influence the design workflow presented in Figure 7-2, and to benefit from the design thinking process by shifting form heritage-centered design to both 'heritage and visitor'-centered design. Thus, the design workflow of phygital heritage should not be a linear process, but designers can go from one phase to another to cover the inspiration, ideation and implementation aspects.

7.7.4. Designing for an Actuated Phygital Heritage

The work in this thesis addressed the augmented category (e.g. *Nimrud Relief*) and the integrated category (e.g. *Saqqara Entrance Colonnade*, *Graethem Chapel*, and *Neferirtenef Tomb-Chapel*) of phygital heritage. Yet, the emerging field of shape-changing technology forms a prime example in the scope of phygital [Rasmussen et al, 2016], which is capable of physically adapting the shape of objects based on users input. Consequently, such technology should be investigated in future studies to address the actuated category in the model illustrated in Figure 7-1, by including immersive and screen-less forms of interaction. We argue that by addressing the actuated phygital category, heritage artefacts might become the output medium as the interface would be embodied by the physical shape, behavior or materiality of the artefact itself. Accordingly, material characteristics of heritage objects might convey meanings by appreciating the physical manifestations of these objects.

7.8. Concluding Remarks

In this thesis, we explored how the phygital approach facilitates the communication of built heritage information. This research resulted in multiple contributions, including (a) a phygital heritage model as an engaging and meaningful medium for communicating heritage information, (b) a design workflow of phygital heritage, (c) four phygital prototypes, (d) six design guidelines, and (e) an evaluation framework for phygital heritage. Moreover, four directions of future work have been highlighted.

We are proud that one of our phygital prototypes has been deployed beyond the research context. The installation of *Neferirtenef Tomb-Chapel* is currently exhibited and available for guided school visits at the Royal Museum of Art and History in Brussels. This example demonstrates that there is a need for a playful and engaging medium of communicating information in the field of heritage.

Furthermore, we demonstrated how our work on heritage communication brings novel design strategies that consider visitors' engagement, situatedness of heritage artifacts, and physical affordance of interfaces. Also, designers of heritage communication can benefit from our design guidelines. In extent, we believe this interdisciplinary research proves how different disciplines learn from and contribute to each other.

Overall, the approach of phygital heritage promises to communicate heritage information in more engaging, educational and meaningful ways. This thesis demonstrates how heritage information can be disclosed via simultaneous and integrated physical and digital means, enabling the broader public to appreciate heritage in more experiential ways.

I

Appendix I:
From Europe to Egypt

This appendix has been previously published as:

Eslam Nofal et al. (2017.b). "From Europe to Egypt: Designing, Implementing and Evaluating Interactive Systems in-the-Wild", Workshop on Designing for the Arab World, *Designing Interactive Systems (DIS '17)*. Edinburgh, UK, 10-14 June 2017.

Abstract

Designing, implementing and evaluating interactive design that is validated in a European context, may deliver different results when being studied in an Arab context, especially when evaluated in-the-wild. In this position paper, we discuss our expectations of two studies that were already conducted in a European context, and will be repeated in an Egyptian context. We reflect on the potential impact of the findings on the design, evaluation methods and initial findings.

I.1. Introduction

Today, HCI research is increasingly evaluated in in-the-wild environments, in which the surrounding context plays an important role in the perception and experience of public interactive systems [Rogers, 2011]. Most of these in-the-wild deployments are evaluated in, and validated for, Western contexts. However, Europe and the United States only represent part of the world. For instance, 508 million citizens live in Europe. Arab countries are inhibited by 422 million persons, and thus represent almost as many potential users as Europe. As such, in-the-wild evaluations of public interactive systems should also be executed in Arab contexts. Here, by the term 'context', we denote the sets of circumstances that are involved in the HCI evaluation process. We categorize these factors into three main categories:

- *User characteristics:* habitual patterns of behavior, personality and emotion (e.g. ability to work, time-value, patience, etc.)
- *Socio-cultural factors:* lifestyle measurements of both financial viability and social standing (e.g. education, religion, income, etc.)
- *Built environment features:* places and spaces that created or modified by people (e.g. the aesthetics of buildings, public spaces, transportation systems, etc.)

No two contexts are the same; not within one country, one city or even one neighborhood. Yet we argue that evaluating design that is validated in a European context, may deliver different results when being studied in an Arab context, especially when evaluated in-the-wild. In this paper, we discuss our expectations of the repeating of two studies that were already conducted in a European context into an Egyptian context, and reflect on the potential impact on the design, evaluation methods and findings.

I.2. Case Studies

Currently, we are preparing the design of two previous studies [Kjeldskov et al, 2004] that have been conducted in a European, in-the-wild context, in order to replicate [Kjeldskov et al, 2004] them in a Egyptian in-the-wild context. In particular, the first study is situated in the semi-public environment of an entrance hall at a university campus in Berlin [Hornbæk et al, 2014] and Cairo. The second study is located inside a public museum in Brussels [Nofal et al, 2017] and might be repeated in another museum in Cairo. The interactive systems of both studies were set-up in these real world environments for several days, and were investigated through observations by a researcher present and video logging, and semi-structured interviews with participants. We believe that when we keep the same design and methodology, thus only change the context of deployment, our previous findings will be predominantly influenced by the contextual circumstances, including user characteristics, socio-cultural factors, and built environment features.

I.3. Discussion

We are aware it is rather difficult to compare findings of two in-the-wild studies with identical design, yet we believe general tendencies can emerge from these deployments, as discussed in the following.

I.3.1. User Characteristics

I.3.1.1. Perception of time

For HCI evaluation studies, time is considered as a challenging aspect [Nofal et al, 2017; Valkanova et al, 2014], especially when evaluating in-the-wild [Hornbæk et al, 2014]. There are recently many endeavors that tackle this challenge by developing novel practices, allowing understanding user requirements in a shortened timeframe. As a matter of fact, time is considered as a cultural concept, our perception of time is influenced by our cultural orientation. Perception of time changes from culture to culture just as languages and behaviors do. Time restrictions of participants are often problematic in-the-wild e.g. when interviewing [Claes et al, 2015.b]. However, we believe it is not such a challenge when we evaluate in in-the-wild Arab countries. For Arab people, time is more flexible and unlimited [Valkanova et al, 2014]. As such, we believe we can capture more and richer qualitative results.

I.3.1.2. Technology experience

Although there is a new 'digital native' generation emerging in Arab countries, technological problems due to basic infrastructure and governments' policies and regulations still exist [Hamade, 2009]. This may cause the participant to focus on the experience with technology rather than the overall experience.

I.3.2. Socio-Cultural Factors

I.3.2.1. Social interaction

The complex values and beliefs that are present in the Arab world provide a rich setting to examine the hypothesized influence of socio-cultural factors on HCI in-the-wild evaluation. For instance, Arabs generally tend to interact as committed members of a group, rather than as independent individuals [Barakat, 1993]. Accordingly, we expect less individual participation in our studies in Egypt compared to group ones, which might lead up to more collaboration and social interaction among participants.

I.3.2.2. Attitudes and behaviors

When the design is not involved in religious taboos or political repression, Arabs tend to express themselves spontaneously and freely in several situations, particularly in those related to human emotions and the arts [Barakat, 1993]. They openly express their likes and dislikes, joy and sadness, etc. As such, we believe that behavioral evaluation methods, such as eye-tracking and observations, would be more effective in the Arab context. On the other hand, instead of low-context communication in Western culture, communication in Arab culture seems to embed the meaning more in the context, as high-context person tend to talk around the point and expect his listener to know what (s)he means [Zaharna, 1995]. Consequently, for attitudinal evaluation methods such as focus groups and interview, the interviewer must understand the contextual cues in order to understand the full meaning of the message.

I.3.2.3. Female participation rate

Women are not eager to be photographed in public because as they are afraid that a photo will be misused, which brings disrespect to her and her family [Abokhodair and Vieweg, 2016]. As such, when there are video recordings for evaluation purposes or photographs used as designed representations, e.g. [Valkanova et al, 2014], we expect the female participation rate will be lower in an Arab context.

I.3.2.4. Social presence

Also social presence is an influential factor in evaluating HCI [Lee and Nass, 2003]. We assume that when we repeat our museum study [Nofal et al, 2017] in Egypt, people would be more involved because it communicates information about an 'Egyptian' built heritage. In such a social context, a collective value can be shared among the participants, which is a unifying concept in designing artifacts and HCI evaluation [Cockton, 2006].

I.3.3. Built Environment

I.3.3.1. Weather conditions

In the European context, outdoor installations might be seriously influenced by the rainy weather conditions [Claes et al, 2015.b; Tieben et al, 2014], which limits user participation and deployment period, and affects the design requirements of the installation. However in the Arab context, the climate is mostly dry, rain is very rare. In contrast, public outdoor installations might be affected during summer by the relatively high temperatures.

I.3.3.2. Crowdedness

In Arab cities, most public spaces such as streets, transport facilities, and shopping malls, are relatively crowded. Crowding has universally negative impacts on individuals [El Sayed et al, 2004], which could be challenging for in-the-wild evaluations of public interactive systems in Arab cities, particularly in Cairo.

However, the crowded environment might also cause honeypot effects, describing how people interact with the systems, which stimulate the others to observe, approach and engage in an interaction [Wouters et al, 2016].

Appendix II: Side Studies

II

Abstract

In this appendix, I report on my participation in various training programs and workshops related to the fields of digital heritage and museum studies during the course of my PhD research.

II.1. Museum Camp

Allard Pierson Museum, Amsterdam, Netherlands

8-10 July, 2016

In July 2016, the first *MuseumCamp* was held in Amsterdam at Allard Pierson Museum. The event involved over 70 participants from the museum domain, exhibition designers and researchers, who worked hard for three intensive days to explore the potential of digital technology for gallery museum exhibits by building 17 interactive installations for 17 selected museum objects.

The event included coaching and the opportunity to gain experience with digital techniques. In a team of five participants, I collaborated with museum makers and designers from the Netherlands and UK (Erik van Tuijn, Tessa de Römph, Karen Tessel, and Geoff Spender) to investigate the possibilities of creating a unique exhibition that incorporates new forms of storytelling about three Egyptian real museum collections from the early medieval period.

I was mainly responsible on the third object in the showcase which was a decorated column capital, having a Greek letters from the other side. I designed a gamified tangible user interface to invite museum visitors to solve a puzzle to complete the wheel of Greek letters as in the original artifact, displayed in a showcase (Figure II-1.a). The interface had an Arduino integrated connected to a mini projector, and accordingly a translation of these Greek letters *"There is one God, the helper of Moses"* is projected on the facing wall, associated with extra information (Figure II-1.b). After that, when visitors rotate the wheel of the interface, another image is projected, which implies that this artifact is double-sided, prompting visitors to see the other side of this artifact (i.e. column capital). Public visitors were invited to visit and to interact with the 17 interactive installations on the last day of the event and for a period of four weeks.

(a) (b)

Figure II-1: *(a) the gamified tangible user interface located in front of the original object in the showcase, and (b) the translation of the Greek letters is projected on the facing wall when a visitor solved the puzzle on the interface.*

II.2. Masterclass: Multimodal Engagements with Cultural Heritage

Maynooth University, Ireland

26-28 September 2016

I have been selected to participate in the Masterclass *"Multimodal Engagements with Cultural Heritage"* organized by An Foras Feasa, the Institute for Research in the Humanities at Maynooth University, Ireland, funded by the DAH PhD Program and PRTLI 5. In this three-day Masterclass, we have been provided with the theoretical background, best practices, and hands-on experience of (a) converting physical objects to digital and printing interactive 3D models, and (b) querying and visualizing online cultural heritage through tangible user interfaces. In the first part of the Masterclass, we learned how to capture cultural artefacts to create 3D models using Structure-from-Motion and laser scanning (Figure II-2.a). We also trained how to process, upload, 3D print digital models, and to design simple interactions between digital and 3D printed objects. In the second part, using Europeana's repositories[1] as an example, we were introduced to the principles of semantic Web, user experience, and interaction design to delve into the new paradigms behind online cultural heritage. Furthermore, we put these skills into action and learned how to provide engaging experiences on the web through a wide range of user interfaces using physical and digital objects (Figure II-2.b).

[1] https://www.europeana.eu/portal/en

(a) (b)

Figure II-2: *Activities conducted in the Masterclass multimodal engagements with cultural heritage(a) training on using Structure-from-Motion to build 3D digital models of heritage artifacts, and (b) querying online heritage repositories using tangible user interface [Perede, 2009].*

II.3. UBISS Summer School

University of Oulu, Oulu, Finland

12-17 June, 2017

In June 2017, I participated in the 8th International UBI Summer School[2] at Oulu University, Finland. After the first day of an opening seminar and lectures, I joined the workshop titled *"Augmented Urban Experience and Mediated Spatial Narratives"* for a period of five days. In which, we had several lectures on the technology of Augmented Reality (AR), its applications, its challenges and the evaluation of user experience with AR. The biggest part of the workshop was devoted to team projects for developing prototypes of using portable (e.g. smartphone or tablet) or warble (e.g. HoloLens) AR device in a certain context.

In a team of four PhD students (Eslam Nofal form KU Leuven; and Mihai Bace, Vincent Becker, and Jing Yang from ETH Zurich), we had an imaginary context of a museum environment, in which two related museum objects were exhibited out of context (Figure II-3.a). In order to blind the digital technologies into the physical reality, we fabricated two physical artifacts (i.e. two pyramids) and we virtually reconstructed the surrounding context (i.e. the third pyramid and the environment around) using Unity 3D platform and Qualcomm Vuforia vision-based tracking SDK. Using the Microsoft HoloLens (a virtual reality (VR) headset with transparent lenses for an augmented reality experience)[3], we managed to contextualize the two physical artifacts by adding visual illustrations and ambient sounds to make the experience of participants more enjoyable and more immersive (Figure II-3.b).

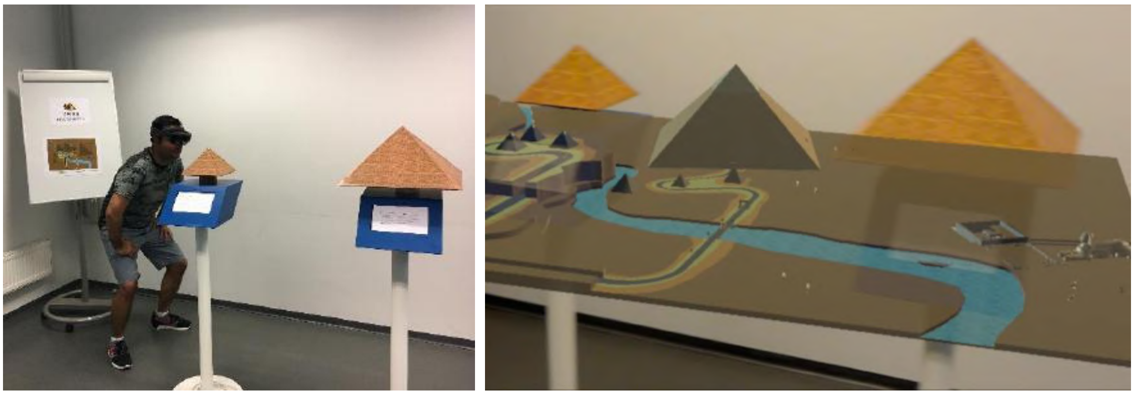
In a class room at the university, we conducted a concise user study that included 5 participants to evaluate our prototype. Participants were invited first to a conventional visit of the artifacts by looking at them and probably reading the labels and the poster beside them. Subsequently, participants were invited to an AR

[2] http://ubicomp.oulu.fi/UBISS

[3] https://www.microsoft.com/sv-SE/hololens

visiting experience by wearing the HoloLens. Their interaction was observed, as they were allowed to look around or to move towards the artifacts. Thereafter, we invited them to fill in a usability questionnaire and to partake in a semi-structured interview that focused on their general impression of the experience, what they learned, and how they described what they have seen.

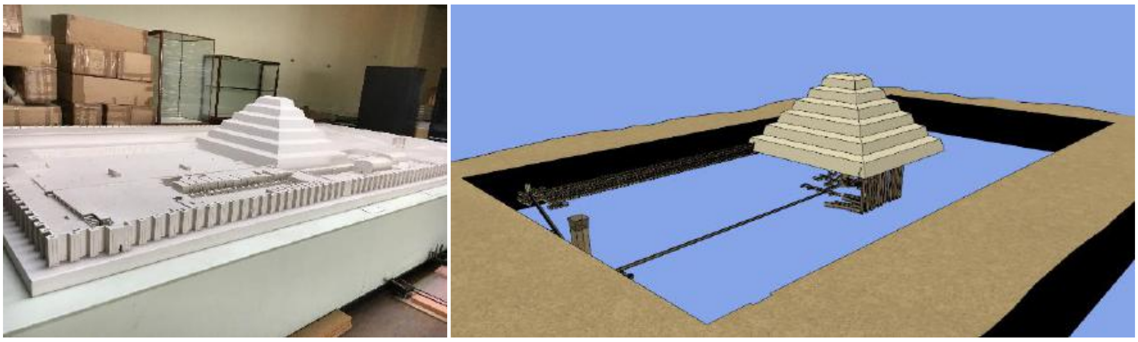
In general, participants highly appreciated the experience as it gave them a better understanding of the context in a very engaging way. They tend to like the idea of moving around the artifacts, looking at them from different point of views. They were astonished by the concept of cutting through the virtual pyramid when they approach it, seeing the hidden tunnels and chambers inside the pyramid and underground. Features of ambient sounds (e.g. wind sound when they approach the desert and water sound when they come closer to the river) and animation (e.g. moving the boat along the river) allowed them to be fully immersed in the experience.



(a) (b)

Figure II-3: *An imaginary context of museum environment to evaluate the prototype of AR HoloLens: (a) one participant is wearing the HoloLens to see the context of the two exhibited artifacts, and (b) a view of what he sees through the HoloLens by augmenting the virtual context into the physical reality.*

Based on the success of this prototype, the same team of four PhD students tried to establish a new collaboration. I proposed a particular case study of the monumental scale model of the Djoser pyramid complex in Saqqara that dates back to 1943 by the Egyptologist Jean-Philippe Lauer. This scale model is part of the Egyptian collection of the Royal Museum of Art and History in Brussels, which was not publically accessible at that time (Figure II-4.a). But the museum has the intention to develop an interactive design to exhibit it to public visitors. Accordingly, I invited the ETH students to present our ideas to the museum curators in Brussels, and to brainstorm with them about which kind of heritage knowledge might be the most suitable to be conveyed to visitors in a meaningful way using HoloLens. The chosen type of information was the visualization of the different building phases of the building to show the visitors the underneath treasures (i.e. tunnels and burial chambers), as illustrated in Figure II-4.b. However, due to the challenge of finding a research question that can be valid to the PhD research of the four collaborators, the study has unfortunately not been continued.



(a) (b)

Figure II-4: *Djoser pyramid complex: (a) the monumental scale model of the complex at the Royal museum of Art and History in Brussels, and (b) a 3D model of the building phases of the complex, showing the underground tunnels and chambers.*

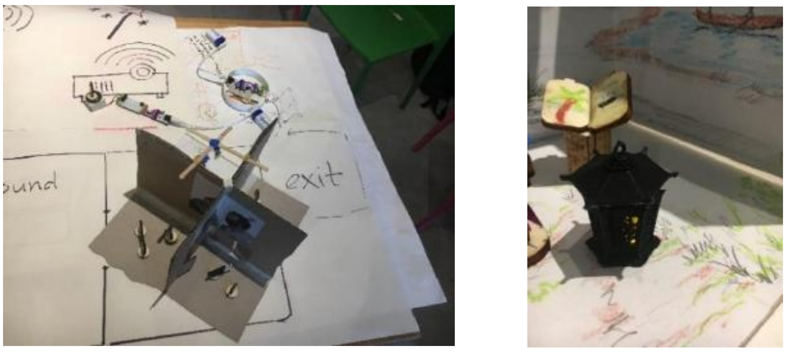
II.4. Museum Camp

NEMO Science Museum, Amsterdam, Netherlands

6-7 July, 2018

Similar to the previous version, in *MuseumCamp* 2018[4] we camped in Nemo Science Museum in Amsterdam for two days to prototype a conceptual idea that tackles one of the museum's challenges. The event involved more than 40 creative museum makers who engaged in new ways of making exhibitions, focusing on the theme: the museum as laboratory.

Among a team of six museum makers from Belgium, Netherlands and Germany (Eslam Nofal, Carolin Freitag, Ceri-Anne van de Geer, Elise Noordhoek, Esther van Gelder, and Ria Winters), we worked in a 48-hour span on a conceptual design of how to exhibit books, creating an immersive experience by combining physical and digital applications. We based our idea on an interactive storytelling technique that triggers museum visitors to spatially navigate in museum spaces to be immersed in the story that the book includes (Figure II-5.a). Visitors are able to activate multimodal content such as visual projection, audio, vibration and even smell using a physical lantern that they can hold during their experience (Figure II-5.b).



(a) (b)

Figure II-5: *A conceptual design of exhibiting books in a museum context: (a) an interactive storytelling technique that triggers museum visitors to spatially navigate in the museum spaces, and (b) the physical lantern that visitors should hold during their experience to activate the content.*

[4] https://www.aanmelder.nl/museumcamp2018

II.5. MuseomixBE

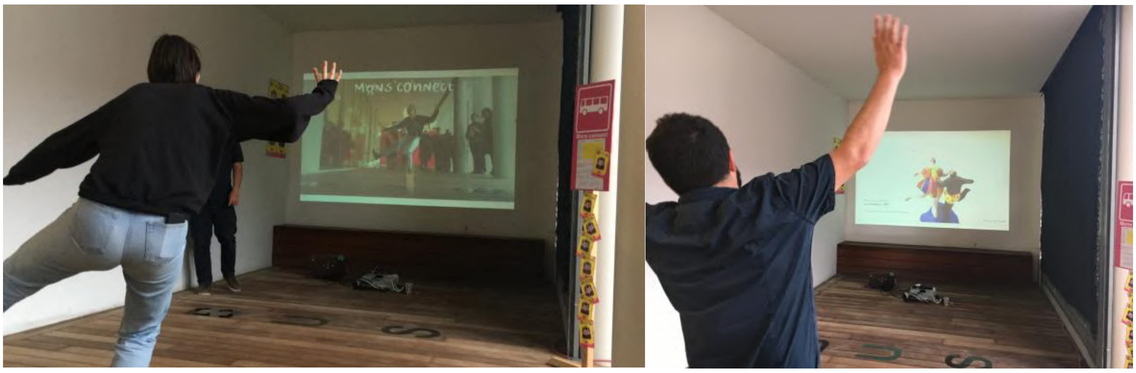
Museum of Fine Arts (BAM), Mons, Belgium

9-11 November, 2018

Museomix is a cultural and technological marathon for three intense days to brainstorm and implement an interactive prototype in teams to tackle one of the challenges that the hosting museum is facing. In November 2018, MuseomixBE[5] took place in the Museum of Fine Arts in Mons (Belgium).

In a team of seven persons who share the same interest of *'making museums'*, we had a challenge of how to connect the collection of the museum with the city, more specifically how to stimulate people in public spaces to know about the museum collections and to interact with. Our roles were defined as; mediation: Nathalie Cimino, graphic design: Ling Wang, communication: Maëlle Stasser, content: Vinciane Godfrind, programming: Samy Rabih, design and making: Eslam Nofal, and facilitation: Claire Allard.

After two sessions of brainstorming, our team *"Mons'connect"* decided to design a prototype that enables the people of Mons to turn from passive receivers to active users by interacting with and reflecting on the artworks of the museum in the city. We developed an interactive prototype that can be located in public space (e.g. billboards at bus stops) by showing on a large display the silhouettes of certain artworks from the museum in a funny way. Passer-by are invited to take the same pose of the artwork's silhouette (Figure II-6.a), and then the display is updated to transform their poses into the artworks of the museum (e.g. statue, painting, etc.) to engage them and to indirectly invite them to visit the museum to know more about the collection (Figure II-6.b).



(a) *(b)*

Figure II-6: *Deploying the design of Mons'connect with real museum visitors: (a) a visitor is trying to take a certain pose according to the displayed silhouette, and (b) a visitor is excited when he successfully fits in the pose and the display is updated to the artwork of the museum.*

Accordingly, we used a Kinect camera connected to a projector and we faked a bus stop in front of the museum (i.e. just beside the main entrance) due to the limited time and to avoid the direct daylight. On the last day of the event, a big number of visitors were invited to come to the museum to see the different interactive

[5] http://museomix.be/

prototypes developed by the different teams. Large number of visitors interacted with our prototype at the beginning of their museum visit. Feedback was mainly positive as visitors found it funny and creative. However, some people did not dare to fit in the pose in public due to social embarrassing.

II.6. Invitation to the British Museum

The British Museum, London, UK

25-28 February, 2019

In February 2019, I received an official invitation from the Department of Ancient Egypt and Sudan at the British Museum in London, funded by Asyut Region project under the Newton Fund partnership. The invitation meant to brainstorm with museum curators and the digital department on how to improve one of the showcases, where tomb assemblages from Asyut are displayed, and how to make it more interactive and visitor-friendly.

Figure II-7.a shows the showcase of the tomb assemblages of Hetepnebi (tomb 56 at Asyut), which is exhibited among the Middle Kingdom collection of Ancient Egypt and Sudan Department at the British Museum. The showcase includes the wooden coffin of Hetepnebi and several objects that were believed to be used in the afterlife such as a seated wooden figure for the owner of the tomb, pottery vessels, wooden figures of a boat's crew, wooden female statuettes, wooden figures of brewers, a pair of sandals, and a headrest.

Through a series of brainstorming sessions, we came up to an intervention proposal that requires a voice recognition of the offerings formula (i.e. hieroglyphics engraved on the coffin) to activate a projected content of the afterlife in ancient Egypt. Thus, the different collections of the showcase can be meaningfully interlinked. The idea of the project has been filmed in an interview (Figure II-7.b). Yet, permissions have to be obtained from the hierarchical management of the museum, and the budget has to be justified and assigned.

(a) *(b)*

Figure II-7: *(a) Showcase of the tomb assemblages of Hetepnebi (tomb 56 at Asyut), and (b) filming a video interview.*

References

Abokhodair, N.; Vieweg, S. (2016). Privacy & social media in the context of the Arab gulf. In Proceedings of the 2016 ACM Conference on Designing Interactive Systems (DIS ’16), Brisbane, QLD, Australia, 4-8 June 2016, pp. 672-683, DOI: https://doi.org/10.1145/2901790.2901873

Addison, A. C. (2001). Virtual heritage: technology in the service of culture. In Proceeding of the 2001 conference on Virtual reality, archeology, and cultural heritage (VAST ’01), Glyfada, Greece, 28-30 November 2001, pp. 343-354, DOI: https://doi.org/10.1145/584993.585055

Alabdulqader, E.; Abokhodair, N.; Lazem, S. (2017). Designing for the Arab world. In Proceedings of the 2017 ACM Conference Companion Publication on Designing Interactive Systems (DIS ’17 Companion), Edinburgh, United Kingdom, 10-14 June 2017, pp. 348-351, DOI: http://dx.doi.org/10.1145/3064857.3064860

Al-Showarah, S.; AL-Jawad, N.; Sellahewa, H. (2014). Effects of user age on smartphone and tablet use, measured with an eye-tracker via fixation duration, scan-path duration, and saccades proportion. In Universal Access in Human-Computer Interaction, Stephanidis C.; Antona M. (Eds). Universal Access to Information and Knowledge. UAHCI 2014. Lecture Notes in Computer Science, Vol. 8514, pp. 3-14, Springer, DOI: https://doi.org/10.1007/978-3-319-07440-5_1

Andrade, F.R.H.; Mizoguchi, R.; Isotani, S. (2016). The bright and dark sides of gamification. In Intelligent Tutoring Systems (ITS2016), Micarelli A.; Stamper J.; Panourgia K. (Eds). Lecture Notes in Computer Science, Vol. 9684, Springer, pp. 176-186, DOI: https://doi.org/10.1007/978-3-319-39583-8_17

Angelopoulou, A.; Economou, D.; Bouki, V.; Psarrou, A.; Jin, L.; Pritchard, C.; Kolyda, F. (2012). Mobile augmented reality for cultural heritage. In Mobile Wireless Middleware, Operating Systems, and Applications (MOBILWARE 2011), Venkatasubramanian N.; Getov V.; Steglich S. (Eds). Lecture Notes of the Institute for Computer Sciences, Social Informatics and Telecommunications Engineering, vol 93, pp. 15-22, Springer, Berlin, Heidelberg, DOI: https://doi.org/10.1007/978-3-642-30607-5_2

Ardito, C.; Buono, P.; Costabile, M.F.; Desolda, G. (2015). Interaction with large displays: A survey. Journal on Computer Surveys (CSUR), 47 (3), Article No. 46, DOI: https://doi.org/10.1145/2682623

Arnold, D. (2003). The Encyclopaedia of Ancient Egyptian Architecture; Princeton University Press: Princeton, NJ, USA.

Azuma, R.; Baillot, Y.; Behringer, R.; Feiner, S.; Julier, S.; MacIntyre, B. (2001). Recent advances in augmented reality. IEEE Computer Graphics and Applications, 21 (6), pp. 34-47, DOI: http://dx.doi.org/10.1109/38.963459

Bafna, S. (2003). Space syntax: a brief introduction to its logic and analytical techniques. Environment and Behaviors, 35 (1), pp. 17-29, DOI: http://dx.doi.org/10.1177/0013916502238863

Bakker, S.; Antle, A.N.; Van Den Hoven, E. (2012). Embodied metaphors in tangible interaction design. Personal and Ubiquitous Computing, 16 (4), pp. 433-449, DOI: https://doi.org/10.1007/s00779-011-0410-4

Barakat, B. (1993). The Arab World: Society, Culture, and State. University of California Press, 1993.

Bazzanella, L.; Roccasalva, G.; Valenti, S. (2014). Phygital public space approach: A case study in Volpiano. Interaction Design and Architecture(s) Journal (IxD&A), 20 (2014), pp. 23-32.

Bederson, B.B. (1995). Audio augmented reality: A prototype automated tour guide. In Proceedings of the Conference Companion on Human Factors in Computing Systems (CHI '95), Denver, CO, USA, 24-28 April 1995, pp. 210-211, DOI: https://doi.org/10.1007/s00779-011-0410-4

Bellotti, F.; Berta, R.; De Gloria, A.; D'ursi, A.; Fiore, V. (2012). A serious game model for cultural heritage. Journal on Computing and Cultural Heritage (JOCCH), 5 (4), pp. 1-27, DOI: https://doi.org/10.1145/2399180.2399185

Bergmans, A. (1998). Middeleeuwse muurschilderingen in de 19de eeuw: Studie en inventaris van middeleeuwse muurschilderingen in Belgische kerken. University Press Leuven, Leuven.

Blikstein, P. (2013). Digital fabrication and 'making' in education: The democratization of invention. In FabLabs: Of Machines, Makers and Inventors, Walter-Herrmann, J.; Büching, C. (Eds). Bielefeld: Transcript Publishers.

Borgo, R.; Abdul-Rahman, A.; Mohamed, F.; Grant, P.W.; Reppa, I.; Floridi, L.; Chen, M. (2012). An empirical study on using visual embellishments in visualization. IEEE Transactions on Visualization and Computer Graphics, 18 (12), pp. 2759-2768, DOI: https://doi.org/10.1109/TVCG.2012.197

Brusaporci, S. (2015). The representation of architectural heritage in the digital age. Encyclopedia of Information Science and Technology, pp. 4195-4206, DOI: http://dx.doi.org/10.4018/978-1-4666-5888-2.ch412

Calixte, X.; Leclercq, P. (2017). The interactive projection mapping as a spatial augmented reality to help collaborative design: Case study in architectural design. In Proceedings of the 14th International Conference on Cooperative Design, Visualization and Engineering (CDVE 2017), Y. Luo (Ed). LNCS 10451, Mallorca, Spain, 17-20 September 2017, pp. 143-152, DOI: https://doi.org/10.1007/978-3-319-66805-5_18

Calvi, L.; Vermeeren, A. (2015). DIY platform for innovative small museum experiences. In Proceedings of the Workshop Cultural Heritage Communities: Technologies & Challenges at the 7th International Conference on Communities and Technologies, Limerick, Ireland, 28 June 2015.

Capurro, C.; Nollet, D.; Pletinckx, D. (2015). Tangible interfaces for digital museum applications: The Virtex and Virtex light systems in the Keys to Rome exhibition. In Proceedings of the Digital Heritage Conference, Granada, Spain, 28 September - 2 October 2015, pp. 271-276, DOI: https://doi.org/10.1109/DigitalHeritage.2015.7413881

Carvalho, M.B.; Bellotti, F.; Berta, R.; De Gloria, A.; Sedano, C.I.; Hauge, J.B.; Hu, J.; Rauterberg, M. (2015). An activity theory-based model for serious games analysis and conceptual design. Computers & Education, 87, September 2015, pp.166-181, DOI: https://doi.org/10.1016/j.compedu.2015.03.023

Cerra, D.; Plank, S.; Lysandrou, V.; Tian, J. (2016). Cultural heritage sites in danger: towards automatic damage detection from space. Remote Sensing, 8 (9), 781, DOI: https://doi.org/10.3390/rs8090781

Chamberlain, A.; Crabtree, A.; Rodden, T.; Jones, M.; Rogers, Y. (2012). Research in the wild: understanding 'in the wild' approaches to design and development. In Proceedings of the Designing Interactive Systems Conference (DIS '12), Newcastle Upon Tyne, UK, 11-15 June 2012, pp. 795-796, DOI: https://doi.org/10.1145/2317956.2318078

Chang, K.; Chang, C.; Hou, H.; Sung, Y.; Chao, H.; Lee, C. (2014). Development and behavioral pattern analysis of a mobile guide system with augmented reality for painting appreciation instruction in an art museum. Computers & Education, 71 (2014), pp. 185-197, DOI: http://dx.doi.org/10.1016/j.compedu.2013.09.022

Chen, S.; Pan, Z.; Zhang, M.; Shen, H. (2013). A case study of user immersion-based systematic design for serious heritage games. Multimedia Tools and Applications, 62 (3), pp. 633-658, DOI: https://doi.org/10.1007/s11042-011-0864-4

Chiapparini, A. (2012) Communication and Cultural Heritage: Communication as Effective Tool for Heritage Conservation and Enhancement. Ph.D. Thesis, Politecnico di Milano University, Milan, Italy.

Chu, J.H.; Clifton, P.; Harley, D.; Pavao, J.; Mazalek, A. (2015). Mapping place: Supporting cultural learning through a Lukasa-inspired tangible tabletop museum exhibit. In Proceedings of the 9th International Conference on Tangible, Embedded, and Embodied Interaction (TEI '15), Stanford, CA, USA, 16-19 January 2015, pp. 261-268, DOI: https://doi.org/10.1145/2677199.2680559

Ciolfi, L.; Petrelli, D.; Goldberg, R.; Dulake, N.; Willox, M.; Marshall, M.T.; Caparrelli. F. (2013). Exploring historical, social and natural heritage: Challenges for tangible interaction design at Sheffield general cemetery. In Proceedings of the NODEM 2013: Beyond Control - The Collaborative Museum and Its Challenges, Stockholm, Sweden, 1-3 December 2013.

Claes, S.; Coenen, J.; Slegers, K.; Vande Moere, A. (2015.a). Design implications of casual health visualization on tangible displays. In Proceedings of the 33rd Annual ACM Conference Extended Abstracts on Human Factors in Computing Systems (CHI EA '15), Seoul, Korea, 18-23 April 2015, pp. 1839-1844, DOI: http://dx.doi.org/10.1145/2702613.2732830

Claes, S.; Wouters, N.; Slegers, K.; Vande Moere, A. (2015.b). Controlling in-the-wild evaluation studies of public displays. In Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems (CHI '15), Seoul, Korea, 18-23 April 2015, pp. 81-84, DOI: http://dx.doi.org/10.1145/2702123.2702353

Claes, S.; Vande Moere, A. (2015). The role of tangible interaction in exploring information on public visualization displays. In Proceedings of the 4th International Symposium on Pervasive Displays (PerDis '15), Saarbrucken, Germany, 10-12 June 2015, pp. 201-207, DOI: https://dl.acm.org/citation.cfm?doid=2757710.2757733

Claes, S.; Vande Moere, A. (2017). Replicating an in-the-wild study one year later: Comparing prototypes with different material dimensions. In Proceedings of the 2017 Conference on Designing Interactive Systems (DIS '17), Edinburgh, UK, 10-14 June 2017, pp. 1321-1325, DOI: https://doi.org/10.1145/3064663.3064725

Cockton, G. (2006). Designing worth is worth designing. In Proceedings of the 4th Nordic conference on Human-computer interaction: changing roles (NordiCHI '06), Oslo, Norway, 14-18 October 2006, pp. 165-174, DOI: http://dx.doi.org/10.1145/1182475.1182493

Coenen, T.; Mostmans, L.; Naessens, K. (2013). MuseUs: Case study of a pervasive cultural heritage serious game. Journal on Computing and Cultural Heritage (JOCCH) - Special issue on serious games for cultural heritage, 6 (2), 2013, Article No. 8, DOI: https://doi.org/10.1145/2460376.2460379

Coomans, Th.; Bergmans, A. (2008). In zuiverheid leven. Het Sint-Agnesbegijnhof van Sint-Truiden: het hof, de kerk, de muurschilderingen (Relicta monografieën, 2). Flemish Institute for Heritage, Brussels.

Coomans, Th. (2011). How tree ring dating can provide historical contexts to buildings 'without history'. In Tree Rings, Art, Archaeology (Scientia Artis,7), Fraiture, P. (Ed). Royal Institute for Cultural Heritage, Brussels, pp. 173-186.

Cosley, D.; Baxter, J.; Lee, S.; Alson, B.; Nomura, S.; Adams, P.; Sarabu, C.; Gay, G. (2009). A tag in the hand: Supporting semantic, social, and spatial navigation in museums. In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '09), Boston, MA, USA, 04-09 April 2009, pp. 1953-1962. DOI: http://dx.doi.org/10.1145/1518701.1518999

Crook, C. (1998). Children as computer users: The case of collaborative learning. Computers & Education, 30 (3-4), pp. 237-247, DOI: https://doi.org/10.1016/S0360-1315(97)00067-5

Csikszentmihalyi, M.; Hemanson, K. (1995). Intrinsic motivation in museums: Why does one want to learn? In Public Institutions for Personal Learning: Establishing a Research Agenda, Falk, J.H.; Dierking, L.D. (Eds), pp. 67-77. Washington, DC: American Association of Museums, Technical Information Service.

Cuneiform Digital Library Initiative (CDLI). (2018). The Northwest Palace at Nimrud, retrieved on April 4th 2017 from: http://cdli.ucla.edu

D'Agnano, F.; Balletti, C.; Guerra, F.; Vernier, P. (2015). Tooteko: A case study of augmented reality for an accessible cultural heritage: Digitization, 3D printing and sensors for an audio-tactile experience. ISPRS - International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Volume XL-5/W4, 2015, pp. 207-213, DOI: https://doi.org/10.5194/isprsarchives-XL-5-W4-207-2015

Damala, A.; Marchal, I.; Houlier, P. (2007). Merging augmented reality based features in mobile multimedia museum guides. In Proceedings of the 21st International CIPA Symposium: Anticipating the Future of the Cultural Past, Athens, Greece, 01-07 October 2007, pp. 259-264, https://halshs.archives-ouvertes.fr/halshs-00530903

Department of Arts, Heritage and the Gaeltacht (D.A.H.G.). (2011). Architectural Heritage Protection: Guidelines for Planning Authorities; The Stationary Office: Dublin, Ireland.

Deterding, S.; Sicart, M.; Nacke, L.; O'Hara, K.; Dixon, D. (2011). Gamification using game-design elements in non-gaming contexts. In Proceedings of the CHI '11 extended abstracts on human factors in computing systems, CHI EA '11, pp. 2425-2428, DOI: https://doi.org/10.1145/1979742.1979575

Dierking, L.D.; Falk, J.H. (1998). Understanding free-choice learning: A review of the research and its application to museum web sites. Museum and the Web. Canada, Retrieved on January 25th, 2019 from: www.museumsandtheweb.com

Doulamis, A.; Doulamis, N.; Ioannidis, C.; Chrysouli, C.; Grammalidis, N.; Dimitropoulos, K.; Potsiou, C.; Stathopoulou, E.K.; Ioannides, M. (2015). 5D modelling: an efficient approach for creating spatiotemporal predictive 3D maps of large-scale cultural resources. ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Volume II-5/W3, Proceedings of the 25th International CIPA Symposium, Taipei, Taiwan, DOI: https://doi.org/10.5194/isprsannals-II-5-W3-61-2015

Dragicevic, P.; Yvonne Jansen, Y. (2012). A Chronological List of Physical Visualizations and Related Artifacts, retrieved online on January 20th 2017 from http://dataphys.org/list/

Dudley, S. (2010). Museum Materialities: Objects, Engagements, Interpretations; Routledge: London, UK; ISBN 978-0415492188

Dunleavy, M.; Dede, C.; Mitchell, R. (2009). Affordances and limitations of immersive participatory augmented reality simulations for teaching and learning. Journal of Science Education and Technology, 18 (1), pp. 7-22, DOI: https://doi.org/10.1007/s10956-008-9119-1

Duranti, D.; Spallazzo, D.; Trocchianesi, R. (2016). Tangible interaction in museums and temporary exhibitions: Embedding and embodying the intangible values of cultural heritage. In Proceedings of the Systems & Design: Beyond Processes and Thinking (IFDP '16), Editorial Universitat Politècnica de València, Valencia, Spain, 22-24 June 2016, pp. 160–171, DOI: https://doi.org/10251/87813

Duranti, D. (2017). Tangible Interaction in Museums and Cultural Heritage Sites: Towards a Conceptual and Design Framework. Ph.D. Thesis, IMT School for Advanced Studies, Lucca, Italy.

El Sayed, I.M.; Farrag, D.A.; Belk, R.W. (2004). The effects of physical surroundings on Egyptian consumers' emotional states and buying intentions. Journal of International Consumer Marketing 16 (1), pp. 5-27, DOI: http://dx.doi.org/10.1300/J046v16n01_02

Englund. K. (2003). Nimrud und seine Funde: Der Weg der Reliefs in die Museen und Sammlungen (Orient-Archäologie, Band 12), Leidorf.

Falk, J. (1998). Visitors: Who does, who doesn't and why. Museum News, 77(2), pp. 38-43.

Falk, J.; Dierking, L. (2002). Lessons without Limit: How Free-Choice Learning is Transforming Education. Walnut Creek: AltaMira Press.

Fallman, D. (2007). Why research-oriented design isn't design-oriented research: On the tensions between design and research in an implicit design discipline. Knowledge, Technology & Policy, 20 (3), pp. 193-200, DOI: https://doi.org/10.1007/s12130-007-9022-8

Fisher, S. (2015). Philosophy of Architecture, Stanford Encyclopedia of Philosophy, retrieved on August 2nd, 2018 from https://plato.stanford.edu/entries/architecture/

Fishkin, K.P. (2004). A taxonomy for and analysis of tangible interfaces. Personal and Ubiquitous Computing, 8 (5), pp. 347-358, DOI: https://doi.org/10.1007/s00779-004-0297-4

Fredheim, L.H.; Khalaf, M. (2016). The significance of values: Heritage value typologies re-examined. International Journal of Heritage Studies, 22 (6), pp. 466-481, DOI: https://doi.org/10.1080/13527258.2016.1171247

Froschauer, J.; Arends, M.; Goldfarb, D.; Merkl, D. (2012). A serious heritage game for art history: Design and evaluation of ThIATRO. In Proceeding of the 18th International Conference on Virtual Systems and Multimedia, Milan, Italy, 2-5 September 2012, pp. 283-290, DOI: https://doi.org/10.1109/VSMM.2012.6365936

Gattinger, M. (2011). Democratization of culture, cultural democracy and governance. In Canadian Public Arts Funders (CPAF) Annual General Meeting, Future Directions in Public Arts Funding: What Are The Shifts Required? Whitehorse, Yukon.

Gaver, W.W.; Beaver, J.; Benford, S. (2003). Ambiguity as a resource for design. In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '03), San Jose, CA, USA, 30 April - 3 May 2003, pp. 233-240, DOI: https://doi.org/10.1145/642611.642653

Genoways, H.H. (2006). Museum Philosophy for the Twenty-First Century; Altamira Press: Lanham, MD, USA; ISBN 978-0759107540

Gillet, A.; Sanner, M.; Stoffler, D.; Olson, A. (2005). Tangible interfaces for structural molecular biology. Structure, 13 (3), pp. 483-491, DOI: https://doi.org/10.1016/j.str.2005.01.009

Häkkilä, J.; Koskenranta, O.; Posti, M.; He, Y. (2014). City landmark as an interactive installation: Experiences with stone, water and public space. In Proceedings of the 8th International Conference on Tangible, Embedded and Embodied Interaction (TEI '14), Munich, Germany, 16-19 February 2014, pp. 221-224, DOI: https://doi.org/10.1145/2540930.2540980

Ham, S.H. (2013). Interpretation—Making a Difference on Purpose. Fulcrum Publishing, Colorado, ISBN: 978-1555917425

Hamade, S.N. (2009). Information and communication technology in Arab countries: Problems and solutions. In Proceedings of the 6th International Conference on Information Technology: New Generations (ITNG '09), Las Vegas, NV, USA, 27-29 April 2009, pp. 1498-1503, DOI: https://doi.org/10.1109/ITNG.2009.62

Hamari, J.; Koivisto, J.; Sarsa, H. (2014). Does gamification work ? A literature review of empirical studies on gamification. In Proceedings of the 47th Hawaii International Conference on System Science, 6-9 January 2014, pp. 3025-3034, DOI: https://doi.org/10.1109/HICSS.2014.377

Hammady, R.; Ma, M.; Temple, N. (2016). Augmented reality and gamification in heritage museums. In Proceedings of the Joint International Conference on Serious Games (JCSG 2016): Serious Games, Marsh, T.; Ma, M.; Oliveira, M.; Baalsrud, Hauge, J.; Göbel, S. (Eds), Springer LNCS 9894, pp. 181-187, DOI: https://doi.org/10.1007/978-3-319-45841-0_17

Hands, G.L.; Stepp, C.E. (2016). Effect of age on human-computer interface control via neck electromyography. Interacting with Computers, 28 (1), pp. 47-54, DOI: https://doi.org/10.1093/iwc/iwu030

Hein, G.E. (1998). Learning in the Museum. London: Routledge, ISBN: 9780415097765

Henderson, T.Z.; Atencio, D.J. (2007). Integration of play, learning, and experience: What museums afford young visitors? Early Childhood Education Journal, 5 (3), pp. 245-251, DOI: https://doi.org/10.1007/s10643-007-0208-1

Henry, D.; Furness, T. (1993). Spatial perception in virtual environments: Evaluating an architectural application. In Proceedings of the IEEE Virtual Reality Annual International Symposium, Seattle, DC, USA, 18-22 September 1993; pp. 33-40, DOI: https://doi.org/10.1109/VRAIS.1993.380801

Hermann. A. (1938). Führer Durch die Altertümer von Memphis und Sakkara. Reichsverlagsamt: Berlin, Germany.

Hooper-Greenhill, E. (1999). The Educational Role of the Museum. Psychology Press, ISBN: 9780415198264

Hooper-Greenhill, E. (2013). Museums and their visitors, Routledge, London.

Hornbæk, K.; Sander, S.S.; Bargas-Avila, J.A.; Simonsen, J.G. (2014). Is once enough? On the extent and content of replications in human-computer interaction. In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '14), Toronto, Ontario, Canada, 26 April - 01 May 2014, pp. 3523-3532, DOI: http://dx.doi.org/10.1145/2556288.2557004

Hornecker, E. (2004). A Design Framework for Designing Tangible Interaction for Collaborative Use. Retrieved January 10, 2019 from http://www.ehornecker.de/Papers/DanishHCI.pdf

Hornecker, E. (2005). A design theme for tangible interaction: Embodied facilitation. In ECSCW 2005, Gellersen H.; Schmidt K.; Beaudouin-Lafon M.; Mackay W. (Eds). Springer, Dordrecht, DOI: https://doi.org/10.1007/1-4020-4023-7_2

Hornecker, E.; Buur, J. (2006). Getting a grip on tangible interaction: A framework on physical space and social interaction. In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '06), Portland, OR, USA, 2-7 April 2006; pp. 437-446, DOI: https://doi.org/10.1145/1124772.1124838

Hou, L.; Wang, X. (2013). A study on the benefits of augmented reality in retaining working memory in assembly tasks: A focus on differences in gender. Automation in Construction, 32 (2013), pp. 38-45, DOI: https://doi.org/10.1016/j.autcon.2012.12.007

Hoyles, C. (1985). What is the point of group discussion in mathematics? Studies in Mathematics, 16 (2), pp. 205-214, DOI: http://www.jstor.org/stable/3482346

Huang W.H.; Soman, D. (2013). A Practitioner's Guide to Gamification of Education. Rotman School of Management, University of Toronto.

Huotari, K.; Hamari, J. (2012). Defining gamification: A service marketing perspective. In Proceeding of the 16th International Academic MindTrek Conference (MindTrek '12), Tampere, Finland, 03-05 October 2012, pp. 17-22, DOI: https://doi.org/10.1145/2393132.2393137

Hurtienne, J.; Israel, J.K. (2007). Image schemas and their metaphorical extensions intuitive patterns for tangible interaction. In Proceedings of the 1st International Conference on Tangible, Embedded, and Embodied Interaction (TEI '07), Baton Rouge, LA, USA, 15-17 February 2007, pp. 127-134, DOI: https://doi.org/10.1145/1226969.1226996

ICOMOS (2008). The ICOMOS Charter for the Interpretation and Presentation of Cultural Heritage Sites. The 16th General Assembly of ICOMOS, Quebec, Canada, 4 October, retrieved on October 1st, 2018 from http://icip.icomos.org/

Ibrahim, N.; Mohamad Ali, N.; Faezah Mohd Yatim, N. (2015). Factors facilitating cultural learning in virtual architectural heritage environments: end user perspective. Journal on Computing and Cultural Heritage (JOCCH), 8 (2), Article 8, DOI: http://dx.doi.org/10.1145/2660776

Ioannidis, Y.; El Raheb, K.; Toli, E.; Katifori, A.; Boile, M.; Mazura, M. (2013). One object many stories: Introducing ICT in museums and collections through digital storytelling. In Proceedings of the 2013 Digital Heritage International Congress (Digital Heritage), Marseilles, France, 28 October - 1 November 2013; pp. 421-424.

Jakobsen, C.L.; Larsen, J.B.; Nørlem, M.L.; Kraus, M. (2018). Improving user experience for lost heritage sites with a user-centered indirect augmented reality application. In Interactivity, Game Creation, Design, Learning, and Innovation, Bressan, F.; Finbow, A.; Vets, T.; Lesaffre, M.; Leman, M. (Eds), pp. 54-63, Springer International Publishing, DOI: https://doi.org/10.1007/978-3-319-76908-0

Jansen, Y.; Dragicevic, P.; Fekete, J.D. (2003). Evaluating the efficiency of physical visualizations. In Proceedings of the ACM Conference on Human Factors in Computing Systems (CHI '13), Paris, France, 27 April - 02 May 2013, pp. 2593-2602, DOI: https://doi.org/10.1145/2470654.2481359

Jansen, Y.; Dragicevic, P.; Isenberg, P.; Alexander, J.; Karnik, A.; Kildal, J.; Subramanianet, S.; Hornbæk, K. (2015). Opportunities and challenges for data physicalization. In Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems (CHI '15), New York, NY, USA, 18-23 April 2015, pp. 3227-3236, DOI: https://doi.org/10.1145/2702123.2702180

Juan, M.C.; Mendez-Lopez, M.; Perez-Hernandez, E.; Albiol-Perez, S. (2014). Augmented reality for the assessment of children's spatial memory in real settings. PLoS ONE, 9 (12): e113751, DOI: https://doi.org/10.1371/journal.pone.0113751

Karayilanoğlu, G.; Arabacioglu, B. C. (2016). The 'new' museum comprehension: "Inclusive museum." In Proceedings of the 2nd International Conference on New Trends in Architecture and Interior Design (ICNTAD 2016), Volume 1, Zagreb, Croatia, 19-22 April 2016, pp. 84-89.

Kelly, L. J. (2007). The Interrelationships between Adult Museum Visitors' Learning Identities and their Museum Experience. PhD Thesis, University of Technology, Sydney, Australia.

Kenderdine, S. (2016). Embodiment, entanglement, and immersion in digital cultural heritage. In A New Companion to Digital Humanities, Schreibman, S.; Siemens, R.; Unsworth, J. (Eds). John Wiley & Sons, Ltd.: New York, NY, USA, 2016; pp. 22–41, DOI: https://doi.org/10.1002/9781118680605.ch2

Kepczynska-Walczak, A.; Walczak, B.M. (2015). Built heritage perception through representation of its atmosphere. Ambiances Experiential Simulation, retrieved online on 21st February 2017 from: http://ambiances.revues.org/640

Kidd, J. (2017). With new eyes I see: Embodiment, empathy and silence in digital heritage interpretation. International Journal of Heritage Studies, 25 (1), pp. 54-66, DOI: https://doi.org/10.1080/13527258.2017.1341946

Kiili, K. (2005). Digital game-based learning: Towards an experiential gaming model. The Internet and Higher Education, 8 (1), pp. 13-24, DOI: https://doi.org/10.1016/j.iheduc.2004.12.001

Kim, D. (2015). Projection mapping contents development of architectural heritage. Advanced Science and Technology Letters, 113, pp. 90-95.

Kim, J.T.; Lee, W. (2015). Dynamical model for gamification of learning (DMGL). Multimedia Tools and Applications, 74 (19), pp. 8483-8493, DOI: https://doi.org/10.1007/s11042-013-1612-8

Kim, S.; Song, K.; Lockee, B.; Burton, J. (2018). What is gamification in learning and education? Gamification in Learning and Education, Advances in Game-Based Learning, Springer International Publishing, pp. 25-38, DOI: https://doi.org/10.1007/978-3-319-47283-6_4

King, L.; Stark, J.F.; Cooke, P. (2016). Experiencing the digital world: The cultural value of digital engagement with heritage. Heritage & Society Journal, 9 (1), pp. 76-101, DOI: https://doi.org/10.1080/2159032X.2016.1246156

Kjeldskov, J., Skov, M.B., Als, B.S., Høegh, R.T. (2004). Is it worth the hassle? Exploring the added value of evaluating the usability of context-aware mobile systems in the field. In Human-Computer Interaction - Mobile HCI 2004, Brewster S.; Dunlop M. (Eds). Lecture Notes in Computer Science, Vol. 3160. Springer, Berlin, Heidelberg, pp. 61-73, DOI: https://doi.org/10.1007/978-3-540-28637-0_6

Kolb, D.A. (1984). Experiential Learning: Experience as the Source of Learning and Development. Englewood Cliffs, NJ: Prentice Hall.

Krautsack, D. (2011). 3D projection mapping and its impact on media & architecture in contemporary and future urban spaces. Journal of the New Media Caucus, summer 2011, 7 (1) "Under Fire: 3D Animation Pedagogy".

Lauer, J.F. (1948). Études Complémentaires sur les Monuments du roi Zoser à Saqqarah (1er Fascicule); Supplément aux Annales du Service des Antiquités de l'Égypte, cahier n° 9; Imprimerie de l'Institut français d'archéologie orientale: Cairo, Egypt.

Laugwitz, B.; Held, T.; Schrepp, M. (2008). Construction and evaluation of a user experience questionnaire. In HCI and Usability for Education and Work (USAB 2008), Holzinger, A. (Ed). Lecture Notes in Computer Science 5298, pp. 63-76, DOI: http://dx.doi.org/10.1007/978-3-540-89350-9_6

Layard, A.H. (1849). Nineveh and its Remains: With an Account of a Visit to the Chaldean Christians of Kurdistan, and the Yezidis, or Devil Worshippers; and an Inquiry into the Manners and Arts of the Ancient Assyrians (2 Volumes), London.

Lee, K.M.; Nass, C. (2003). Designing social presence of social actors in human computer interaction. In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '03), Ft. Lauderdale, Florida, USA, 05-10 April 2003, pp. 289-296, DOI: http://dx.doi.org/10.1145/642611.642662

Li, A.C.; Liew, A.W.C.; and Su, W.P. (2012). The digital museum: Challenges and solutions. In Proceedings of the 8th International Conference on Information Science and Digital Content Technology (ICIDT2012), Jeju Island, South Korea, 26-28 June 2012, pp. 646-649, DOI: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6269353&isnumber=6269316

Light, D. (1996). Characteristics of the audience for 'events' at a heritage site. Tourism Management, 17 (3), pp. 183-190, DOI: http://dx.doi.org/10.1016/0261-5177(96)00005-2

Lupetti, M.L.; Piumatti, G.; Rossetto, F. (2015). Phygital play HRI in a new gaming scenario. In Proceedings of the 7th International Conference on Intelligent Technologies for Interactive Entertainment (INTETAIN), Turin, Italy, 10-12 June 2015, pp. 17-21, DOI: https://doi.org/10.4108/icst.intetain.2015.259563

Lux, G.V.; Bussels, M. (1969). De opgravingen in en om de kapel van het gasthuis te Borgloon. In Het Oude Land van Loon 24, pp. 163-225.

Ma, J.; Sindorf, L.; Liao, I.; Frazier, J. (2015). Using a tangible versus a multi-touch graphical user interface to support data exploration at a museum exhibit. In Proceedings of the 9th International Conference on Tangible, Embedded, and Embodied Interaction (TEI '15), Stanford, California, USA, 15-19 January 2015, pp. 33-40, DOI: https://doi.org/10.1145/2677199.2680555

Macaranas, A.; Antle, A.N.; Riecke, B.E. (2012). Bridging the gap: attribute and spatial metaphors for tangible interface design. In Proceedings of the 6th International Conference on Tangible, Embedded and Embodied Interaction (TEI '12), Kingston, Ontario, Canada, 19-22 February 2012, pp. 161-168, DOI: https://doi.org/10.1145/2148131.2148166

Mantova. (2016). Capitale Italiana della Cultura: Mantova Phygital City project, retrieved online on January 20th 2017 from: http://www.mantova2016.it/it-ww/mantova-phygital-city.aspx

Marshall, M.T.; Dulake, N.; Ciolfi, L.; Duranti, D.; Kockelkorn, H.; Petrelli, D. (2016). Using tangible smart replicas as controls for an interactive museum exhibition. In Proceedings of the 10th International Conference on Tangible, Embedded, and Embodied Interaction (TEI '16), Eindhoven, The Netherlands, 14-17 February 2016, pp. 159-167, DOI: https://doi.org/10.1145/2839462.2839493

Marshall, P. (2007). Do tangible interfaces enhance learning? In Proceedings of the 1st International Conference on Tangible and embedded interaction (TEI '07), Baton Rouge, Louisiana, USA, 15-17 February 2007, pp. 163-170, DOI: https://doi.org/10.1145/1226969.1227004

Marton, F.; Rodriguez, M.B.; Bettio, F.; Agus, M.; Villanueva, A.J.; Gobbetti, E. (2014). IsoCam: Interactive visual exploration of massive cultural heritage models on large projection setups. Journal Computing on Cultural Heritage (JOCCH), 7 (2), Article No. 12, DOI: https://doi.org/10.1145/2611519

Massart, C. (2014). Digitale Reconstructie Van De Bouwfasen Van De Graethemkapel Te Borgloon (Unpublished Master Thesis). Faculty of Engineering Science, KU Leuven, Belgium.

Milgram, P.; Kishino, F. (1994). A taxonomy of mixed reality visual displays. IEICE Transactions on Information and Systems, 77 (12), pp. 1321-1329.

Milne, L. (2011). The Significance of Aesthetic and Heritage Values in a Public Policy Environment: Victoria Theatre Case Study. Master's Thesis, Auckland University of Technology, Auckland, New Zealand.

Mine, M.R.; Van Baar, J.; Grundhofer, A.; Rose, D., Yang, B. (2012). Projection-based augmented reality in Disney theme parks. IEEE Computer, 45 (7), pp. 32-40, DOI: http://dx.doi.org/10.1109/MC.2012.154

Mohammed-Amin, R.K. (2015). Augmented Experiences: What Can Mobile Augmented Reality Offer Museums and Historic Sites (PhD Thesis), University of Calgary, Alberta, Canada, DOI: http://dx.doi.org/10.5072/PRISM/25067

Mourkoussis, N.; Liarokapis, F.; Darcy, J.; Pettersson, M.; Petridis, P.; Lister, P.F.; White, M. (2002). Virtual and augmented reality applied to educational and cultural heritage domains. In Business Information Systems, Proceedings of BIS 2002, Abramowicz, W. (Ed), Poznan, Poland, pp. 367-372.

Nakazawa, J.; Tokuda, H. (2007). Phygital map: Accessing digital multimedia from physical map. In Proceedings of the 21st International Conference on Advanced Information Networking and Applications Workshops (AINAW '07), Niagara Falls, Ont., Canada, 21-23 May 2007, pp. 368-373, DOI: https://doi.org/10.1109/AINAW.2007.288

Nastasi, B.K.; Clements, D. H. (1992). Social-cognitive behaviours and higher-order thinking in educational computer environments. Learning and Instruction, 2 (3), pp. 215-238, DOI: https://doi.org/10.1016/0959-4752(92)90010-J

Nesbitt, K. (1996). Theorizing a New Agenda for Architecture: An Anthology of Architectural Theory 1965 – 1995. Princeton Architectural Press, ISBN: 156898054X, 9781568980546

Nofal, E. (2013). Taking advantages of augmented reality technology in museum visiting experience. In Proceedings of the 6th International Congress Science and Technology for the Safeguard of Cultural Heritage in the Mediterranean Basin, Athens, Greece, 22-25 October 2013,

Nofal, E.; Boschloos, V.; Hameeuw, H.; Vande Moere, A. (2016). The role of tangible interaction for communicating qualitative information of built heritage. In Proceedings of the 8th International Congress on Archaeology, Computer Graphics, Cultural Heritage and Innovation (Arqueológica 2.0), Valencia, Spain, 5-7 September 2016; pp. 441-444.

Nofal, E.; Reffat, R.M.; Vande Moere, A. (2017.a). Communicating built heritage information using tangible interaction approach. In Proceedings of the 11th International Conference on Tangible, Embedded, and Embodied Interaction (TEI ’17), Yokohama, Japan, 20-23 March 2017, pp. 689-692, DOI: https://doi.org/10.1145/3024969.3025035

Nofal E.; Claes S.; Vande Moere A. (2017.b). From Europe to Egypt: Designing, implementing and evaluating interactive systems in-the-wild. Workshop on Designing for the Arab World, Designing Interactive Systems (DIS ’17). Edinburgh, UK, 10-14 June 2017.

Nofal, E.; Reffat, R.M.; Vande Moere, A. (2017.c). Phygital heritage: An approach for heritage communication. In Proceedings of the 3rd Immersive Learning Research Network Conference (iLRN2017), Coimbra, Portugal, 26-29 June 2017, pp. 220-229, DOI: https://doi.org/10.3217/978-3-85125-530-0-36

Nofal, E.; Reffat, R. M.; Boschloos, V.; Hameeuw, H.; Vande Moere, A. (2018.a). The role of tangible interaction to communicate tacit knowledge of built heritage. Heritage 2018, 1 (2), pp. 414-436, DOI: https://doi.org/10.3390/heritage1020028

Nofal E.; Elhanafi A.; Hameeuw H.; Vande Moere A. (2018.b). Architectural contextualization of heritage museum artifacts using augmented reality. Studies in Digital Heritage (SDH), 2(1), 42-67, DOI: https://doi.org/10.14434/sdh.v2i1.24500

Nofal E.; Stevens R.; Coomans T.; Vande Moere A. (2018.c). Communicating the spatiotemporal transformation of architectural heritage via an in-situ projection mapping installation. Digital Applications in Archaeology and Cultural Heritage (DAACH), 11C (2018) e00083, DOI: https://doi.org/10.1016/j.daach.2018.e00083

Nofal, E.; Panagiotidou, G.; Reffat, R. M.; Hameeuw, H.; Boschloos, V.; Vande Moere, A. (under review). Situated tangible gamification of heritage for supporting collaborative learning of young museum visitors. ACM Journal on Computing and Cultural Heritage (JOCCH).

Norman, D.A. (1998). The Invisible Computer: Why Good Products Can Fail, the Personal Computer is so Complex, and Information Appliances are the Solution. MIT Press Cambridge, MA, USA, ISBN: 0-262-14065-9

Norris, N. (1997). Error, bias and validity in qualitative research. Educational Action Research, 5 (1), pp. 172-176, DOI: https://doi.org/10.1080/09650799700200020

Not, E.; Cavada, D.; Maule, S.; Pisetti, A.; Venturini, A. (2019). Digital augmentation of historical objects through tangible interaction. Journal on Computing and Cultural Heritage (JOCCH), in press.

Oates, J.; Oates, D. (2001). Nimrud: An Assyrian Imperial City Revealed. British School of Archaeology in Iraq, ISBN: 978-0903472258

Paley, S.M. (2002). Creating a virtual reality model of the North-West Palace. Nimrud Conference: New Light on Nimrud, Curtis, J.E.; McCall, H.; Collon, D.; al-Gailani Werr, L. (Eds). London, UK, 11-13 March 2002, pp. 195-208, ISBN: 978-0903472241

Paris, S.G. (1997). Situated motivation and informal learning. Journal of Museum Education, 22 (2-3), pp. 22-27. DOI: https://doi.org/10.1080/10598650.1997.11510356

Pereda, J. (2019). A TUI to explore cultural heritage repositories on the web. In Proceedings of the 13th International Conference on Tangible, Embedded, and Embodied Interaction (TEI '19), Tempe, Arizona, USA, 17-20 March 2019, pp. 259-267, DOI: https://doi.org/10.1145/3294109.3301000

Petrelli, D.; Ciolfi, L.; Van Dijk, D.; Hornecker, E.; Not, E.; Schmidt, A. (2013). Integrating material and digital: A new way for cultural heritage. ACM Interaction Magazine, 20 (4), pp. 58-63, DOI: https://doi.org/10.1145/2486227.2486239

Petrelli, D.; Lechner, M. (2014). The meSch project - Material encounters with digital cultural heritage: Reusing existing digital resources in the creation of novel forms of visitor's experiences. In Proceedings of the Annual Conference of CIDOC: The International Committee for Documentation of ICOM, Dresden, Germany, 06-11 September 2014, pp.01-10.

Piscitelli, B.; Anderson, D. (2001). Young children's perspectives of museum settings and experiences. Museum Management and Curatorship, 19 (3), pp. 269-282, DOI: https://doi.org/10.1080/09647770100401903

Pollalis, C.; Fahnbulleh, W.; Tynes, J.; Shaer, O. (2017). HoloMuse: Enhancing engagement with archaeological artifacts through gesture-based interaction with holograms. In Proceedings of the 11th International Conference on Tangible, Embedded, and Embodied Interaction (TEI '17), Yokohama, Japan, 20-23 March 2017, pp. 565-570, DOI: https://doi.org/10.1145/3024969.3025094

Price, S.; Rogers, Y.; Scaife, M.; Stanton, D.; Neale, H. (2003). Using 'tangibles' to promote novel forms of playful learning. Interacting with Computers, 15 (2), pp. 169-185, DOI: https://doi.org/10.1016/S0953-5438(03)00006-7

Rapetti, G. (2005). Frammenti di Memoria. Festival Artistico "Villaggio Delle Lanterne", retrieved online on June 20th 2018 from: https://gabrielrapetti.com/frammenti-di-memoria/

Raskar, R.; Welch, G.; Fuchs, H. (1998). Spatially augmented reality. In Proceedings of the 1st IEEE Workshop on Augmented Reality (IWAR '98): Placing Artificial Objects in Real Scenes, pp. 63-72.

Rasmussen, M.K.; Merritt, T.; Alonso, M.B.; Petersen, M. G. (2016). Balancing user and system control in shape-changing interfaces: A designerly exploration. In Proceedings of the 10th International Conference on Tangible, Embedded, and Embodied Interaction (TEI '16), Eindhoven, The Netherlands, 14-17 February 2016, pp. 202-210, DOI: https://doi.org/10.1145/2839462.2839499

Rauschenberger, M.; Schrepp, M.; Pérez Cota, M.; Olschner, S.; Thomaschewski, J. (2013). Efficient measurement of the user experience of interactive products: how to use the user experience questionnaire (UEQ) - example: Spanish language version. International Journal of Interactive Multimedia and Artificial Intelligence, 2 (1), pp. 39-45, DOI: http://dx.doi.org/10.9781/ijimai.2013.215

Reffat, R.M.; Nofal, E. (2013). Effective communication with cultural heritage using virtual technologies. International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Volume XL-5/W2, pp. 519-524, DOI: https://doi.org/10.5194/isprsarchives-XL-5-W2-519-2013

Rekimoto, J.; Ayatsuka, Y.; Hayashi, K. (1998). Augment-able reality: Situated communication through physical and digital Spaces. In Proceedings of the 2nd IEEE International Symposium on Wearable Computers (ISWC '98), Pittsburgh, PA, USA, pp. 68-75, 19-20 October 1998, DOI: https://doi.org/10.1109/ISWC.1998.729531

Ridel, B.; Reuter, P.; Laviole, J.; Mellado, N.; Couture, N.; Granier, X. (2014). The revealing flashlight: interactive spatial augmented reality for detail exploration of cultural heritage artifacts. Journal on Computing and Cultural Heritage (JOCCH), Special Issue Interacting with the Past, 7 (2), Article No. 6, DOI: http://dx.doi.org/10.1145/2611376

Rodéhn, C. (2015). Democratization: The performance of academic discourses on democratizing museums. In Heritage Keywords: Rhetoric and Redescription in Cultural Heritage, Samuels, K.L.; Rico, T. (Eds). University Press of Colorado, pp. 95-110, ISBN 978-1-60732-383-9

Rogers, Y. (2011). Interaction design gone wild: striving for wild theory. Interactions Magazine, 18, (4), pp. 58-62, DOI: http://dx.doi.org/10.1145/1978822.1978834

Rohlfing, K.; Rehm, M.; Goecke, K.U. (2003). Situatedness: The interplay between context(s) and situation. Journal of Cognition and Culture, 3 (2), pp. 132-156, DOI: https://doi.org/10.1163/156853703322148516

Roussou, M. (2002). Virtual heritage: from the research lab to the broad public. Virtual Archeology: Proceedings of the VAST 2000 Euroconference, Niccolucci F. (Ed.), ACM Press, Arezzo, Italy, pp. 93-100.

Rubegni, E.; Di Blas, N.; Paolini, P.; Sabiescu, A. (2010). A Format to design narrative multi-media applications for cultural heritage communication. In Proceedings of the 2010 ACM Symposium on Applied Computing (SAC '10), Sierre, Switzerland, 22-26 March 2010, pp. 1238-1239, DOI: https://doi.org/0.1145/1774088.1774350

Sadalla, E.K.; Oxley, D. (1984). The perception of room size: The rectangularity illusion. Environment and Behavior, 16(3), pp. 394-405, DOI: https://doi.org/10.1177/0013916584163005

Salen, K.; Zimmerman, E. (2004). Rules of Play: Game Design Fundamentals. The MIT Press Cambridge, Massachusetts, ISBN: 978-0262240451

Scruton, R. (2013). The Aesthetics of Architecture 2nd edition. Princeton University Press, Princeton.

Seo, J.H.; Arita, J.; Chu, S.; Quek, F.; Aldriedge, S. (2015). Material significance of tangibles for young children. In Proceedings of the 9th International Conference on Tangible, Embedded, and Embodied Interaction (TEI '15), Stanford, CA, USA, 16-19 January 2015, pp. 53-56, DOI: https://doi.org/10.1145/2677199.2680583

Shaer, O.; Hornecker, E. (2010). Tangible user interfaces: past, present, and future directions. Foundations and Trends in Human-Computer Interaction 3 (1-2), pp. 4-137, DOI: http://dx.doi.org/10.1561/1100000026

Simon, N. (2010). The participatory Museum. Museum 2.0: Santa Cruz, CA, USA, ISBN-13: 978-0-615-34650-2

Simons, W. (2003). Cities of Ladies: Beguine Communities in the Medieval Low Countries 1200-1565. University of Pennsylvania Press, Philadelphia.

Sitzia, E. (2016). Narrative theories and learning in contemporary art Museums: A theoretical exploration. Stedelijk Studies, 2016 (4), pp. 1-15.

Smith, A. (2010). The Value of Built Heritage. The College of Estate Management; Occasional Papers Series, retrieved online on November 2nd 2017 from: https://www.ucem.ac.uk/

Stanco, F.; Tanasi, D.; Buffa, M.; Basile, B. (2012). Augmented perception of the past: The case of the Telamon from the Greek theater of Syracuse. In Multimedia for Cultural Heritage, Grana C.; Cucchiara R. (Eds). Communications in Computer and Information Science, vol 247, pp. 126-135, Springer, Berlin, Heidelberg, DOI: https://doi.org/10.1007/978-3-642-27978-2_11

Stevens, R. (2017). Communicating Architectural Heritage Through an Interactive In-Situ Projection Mapping Installation. Graethemkapel (Unpublished Master Thesis). Faculty of Engineering Science, KU Leuven, Belgium.

Sueishi, T.; Oku, H.; Ishikawa, M. (2016). Lumipen 2: Dynamic projection mapping with mirror-based robust high-speed tracking against illumination changes. Journal of Presence: Teleoperators and Virtual Environments Archive, 24 (4), pp. 299-321, DOI: http://dx.doi.org/10.1162/PRES_a_00275

Sun, Q.; Ardito, C.; Buono, P.; Costabile, M.F.; Lanzilotti, R.; Pederson, T.; Piccinno, A. (2008). Experiencing the past through the senses: An M-learning game at archaeological parks. IEEE MultiMedia, 15 (4), pp. 76-81, DOI: https://doi.org/10.1109/MMUL.2008.87

Suzuki, H.; Kato, H. (1995). An educational tool for collaborative learning: AlgoBlock. Cognitive Studies, 2 (1), pp. 36-47, DOI: https://doi.org/10.11225/jcss.2.1_36

Tan, B. K.; Rahaman, H. (2009) Virtual heritage: reality and criticism. In Proceedings of CAADFutures 2009: Joining Languages, Cultures and Visions, Tidafi, T.; Dorta, T. (Eds), Les Presses de l'Université de Montréal (PUM), pp. 143-156, ISBN: 978-2760621770

Taylor, R.; Bowers, J.; Nissen, B.; Wood, G.; Chaudhry, O.; Wright, P.; Bruce, L.; Glynn, S.; Mallinson, H.; Bearpark, R. (2015). Making magic: Designing for open interactions in museum settings. In Proceedings of the ACM SIGCHI Conference on Creativity and Cognition (C&C '15), Glasgow, UK, 22-25 June 2015, pp. 313-322, DOI: https://doi.org/10.1145/2757226.2757241

Teo, V. (2013). The Internet of Things: Let's Get Phygital, retrieved online on July 25th 2016 from: https://www.clickz.com/the-internet-of-things-lets-get-phygital/39692/

Tieben, R.; de Valk, L.; Rijnbout, P.; Bekker, T.; Schouten, B. (2014). Shake up the schoolyard: Iterative design research for public playful installations. In Proceedings of the 2014 Conference on Interaction Design and Children (IDC '14), Aarhus, Denmark, 17-20 June 2014, pp. 175-183, DOI: http://dx.doi.org/10.1145/2593968.2593980

Tillon, A.B.; Marchal, I.; Houlier, P. (2011). Mobile augmented reality in the museum: Can a lace-like technology take you closer to works of art? In Proceedings of IEEE International Symposium on Mixed and Augmented Reality - Arts, Media, and Humanities, Basel, Switzerland, 26-29 October 2011, pp. 41-47, DOI: http://dx.doi.org/10.1109/ISMAR-AMH.2011.6093655

Thompson, C. (1994). The role of the museum in interpretation: The problem of context. International Journal of Heritage Studies, 1(1), pp. 40-51, DOI: https://doi.org/10.1080/13527259408722129

Touch Graphics. (2015). San Diego Museum of Art Talking Tactile Exhibit Panel, retrieved online on June 30th 2018 from: http://touchgraphics.com/portfolio/sdma-exhibit-panel/

Tweed, C.; Sutherland, M. (2007). Built cultural heritage and sustainable urban development. Landscape and Urban Planning, 83 (1), pp. 62-69, DOI: https://doi.org/10.1016/j.landurbplan.2007.05.008

Ullmer, B.; Ishii, H. (2000). Emerging Frameworks for Tangible User Interfaces. IBM Systems Journal, 39 (3.4), pp. 915-931, DOI: https://doi.org/10.1147/sj.393.0915

Uspenski, I. (2013) Shared in confidence: A machine to a machine (The Birth of post-semantic aesthetics). In Proceedings of the International Conference Beyond AI: Artificial Golem Intelligence, Romportl, J.; Ircing, P.; Zackova, E.; Polak, M.; Schuster, R. (Eds), Pilsen, Czech Republic, 12-14 November 2013, pp. 41-57, ISBN 978-80-261-0275-5

Valkanova, N.; Walter, R.; Vande Moere, A.; Müller, J. (2014). Myposition: sparking civic discourse by a public interactive poll visualization. In Proceedings of the 17th ACM conference on Computer Supported Cooperative Work & Social Computing (CSCW '14), Baltimore, Maryland, USA, 15-19 February 2014, pp. 1323-1332, DOI: http://dx.doi.org/10.1145/2531602.2531639

Valkanova, N.; Claes, S.; Behrens, M.; Vande Moere, A. (2015). Information-bombing: Con-fronting the public to civic data. In Workshop on Beyond Personal Informatics: De-signing for Experiences with Data, co-located with CHI '15, pp. 18-23, April 2015, Seoul, Korea.

Van Balen, K. (2008). The Nara grid: An evaluation scheme based on the Nara document on authenticity. The Association for Preservation Technology International (APT bulletin), 49 (10), pp. 39-45, ISSN: 0848-8525

Van de Walle, B. (1978). Lachapelle Funéraire de Neferirtenef, Musées royaux d'Art et d'Histoire, Bruxelles.

Van der Vaart, M.; Damala, A. (2015). Through the Loupe: Visitor engagement with a primarily text-based handheld AR application. In Proceedings of the Digital Heritage Conference, Granada, Spain, 28 September - 2 October 2015, pp. 565-572, DOI: https://doi.org/10.1109/DigitalHeritage.2015.7419574

Van Rinsveld, B. (1997). Une Maquette Monumentale au Musée du Cinquantenaire: Le Complexe Funéraire de Djoser à Saqqara. Bull. R. Mus. Art Hist. Brussels, 68, pp. 43-54.

Vande Moere, A.; Wouters, N. (2012). The role of context in media architecture. In Proceedings of the 2012 International Symposium on Pervasive Displays (PerDis '12), Article No. 12, 4-5 June 2012, Porto, Portugal, DOI: https://doi.org/10.1145/2307798.2307810

Vlahakis, V.; Ioannidis, N.; Karigiannis, J.; Tsotros, M.; Gounaris, M.; Stricker, D.; Gleue, T.; Daehne, P.; Almeida, L. (2002). Archeoguide: an augmented reality guide for archaeological sites. IEEE Computer Graphics and Applications Archive, 22 (5), pp. 52-60. http://dx.doi.org/10.1109/MCG.2002.1028726

Vermeeren, A.; Calvi, L.; Sabiescu, A.; Trocchianesi, R.; Stuedahl, D.; Giaccardi, E.; Radice, S. (2018). Museum experience design: Crowds, ecosystems and novel technologies. In Museum Experience Design, Vermeeren A., Calvi L., Sabiescu A. (Eds). Springer Series on Cultural Computing. Springer, pp.1-16, DOI: https://doi.org/10.1007/978-3-319-58550-5_1

Vermeersch, P., Schijlen, J., Heylighen, A. (2018). Designing from disability experience: Space for multi-sensoriality. In Proceedings of the 15th Participatory Design Conference: Short Papers, Situated Actions, Workshops and Tutorial - Volume 2, Article No. 22, Hasselt and Genk, Belgium, 20-24 August 2018, DOI: https://doi.org/10.1145/3210604.3210622

Verner, M. (2001). The Pyramids: The Mystery, Culture and Science of Egypt's Great Monuments; Grove/Atlantic, Inc.: New York, NY, USA.

Voigt, A.; Martens, B. (2006). Development of 3D tactile models for the partially sighted to facilitate spatial orientation. In Proceedings of the 24th eCAADe Conference: Communicating Space(s), Ljubljana, Slovenia, 21-24 September 2006; pp. 366-370.

Vongsingthong, S.; Smanchat, S. (2014). Internet of Things: A review of applications and technologies. Suranaree Journal of Science and Technology, 21 (4), pp. 359-374, DOI: https://doi.org/10.14456/sjst.2014.38

Wakkary, R.; Hatala, M.; Muise, K.; Tanenbaum, K.; Corness, G.; Mohabbati, B.; Budd, J. (2009). Kurio: A museum guide for families. In Proceedings of the 3rd International Conference on Tangible and Embedded Interaction (TEI '09), Cambridge, UK, 16-18 February 2009, pp. 215-222, DOI: https://doi.org/10.1145/1517664.1517712

Waldek, S. (2016). The Metropolitan Museum's Temple of Dendur Plays Host to a Dazzling Light Show. An online resource, retrieved on July 25th, 2018 from: https://www.architecturaldigest.com/story/temple-of-dendur-color-metropolitanmuseum

Wania, C.E.; Atwood, M.E.; McCain; K.W. (2006). How do design and evaluation interrelate in HCI research? In Proceedings of the 6th conference on Designing Interactive systems (DIS '06), University Park, PA, USA, 26-28 June 2006, pp. 90-98, DOI: https://doi.org/10.1145/1142405.1142421

Willett, W.; Jansen, Y.; Dragicevic, P. (2017). Embedded data representations. IEEE Transactions on Visualization and Computer Graphics, 23 (1), pp. 461-470, DOI: https://doi.org/10.1109/TVCG.2016.2598608

Wojciechowski, R.; Walczak, K.; White, M.; Cellary, W. (2004). Building virtual and augmented reality museum exhibitions. In Proceedings of the 9th International

Conference on 3D Web Technology (Web3D ’04), Monterey, California, 5-8 April 2004, pp. 135-144, DOI: http://doi.acm.org/10.1145/985040.985060

Wouters, N.; Downs, J.; Harrop, M.; Cox, T.; Oliveira, E.; Webber, S.; Vetere, F.; Vande Moere, A. (2016). Uncovering the honeypot effect: how audiences engage with public interactive systems. In Proceedings of the 2016 ACM Conference on Designing Interactive Systems (DIS ’16), Brisbane, QLD, Australia, 4-8 June 2016, pp. 5-16, DOI: https://doi.org/10.1145/2901790.2901796

Wyeth, P. (2008). Understanding engagement with tangible user interfaces. In Proceedings of the 20th Australasian Conference on Computer-Human Interaction (OZCHI ’08): Designing for Habitus and Habitat, Cairns, Australia, 8-12 December 2008, pp. 331-334, DOI: https://doi.org/10.1145/1517744.1517810

Yilmaz, R.M. (2016). Educational magic toys developed with augmented reality technology for early childhood education. Computers in Human Behavior, 54 (2016), pp. 240-248, DOI: http://dx.doi.org/10.1016/j.chb.2015.07.040

Zaharna, R. S. (1995). Understanding cultural preferences of Arab communication patterns. Public Relations Review, 21 (3), pp. 241-255, DOI: https://doi.org/10.1016/0363-8111(95)90024-1

Zumthor, P. (2006). Atmospheres: Architectural Environments. Surrounding Objects. Birkhauser, ISBN: 9783764374952

FACULTY OF ENGINEERING SCIENCE
DEPARTMENT OF ARCHITECTURE
RESEARCH[X]DESIGN
Kasteelpark Arenberg 1
B-3001 HEVERLEE, BELGIUM
eslam.nofal@kuleuven.be
eslam.nofal@aun.edu.eg
http://rxd.architectuur.kuleuven.be/