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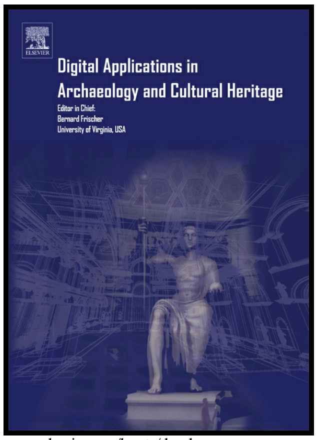

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Communicating the Spatiotemporal Transformation of Architectural Heritage via an In-Situ Projection Mapping Installation

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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.

Keywords: Projection mapping; tangible user interface (TUI); architectural heritage; spatiotemporal transformation; heritage communication; *in-situ* installation.

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 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.

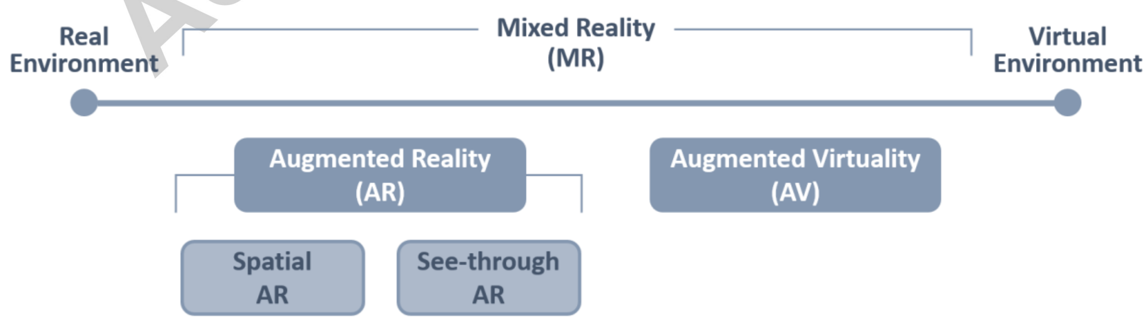


Figure 1. AR techniques on Milgram's Reality-Virtuality continuum that apt in communicating heritage information in-situ [Authors after Milgram and Kishino, 1994; Ridel et al., 2014].

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]. 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 2.f), was intended as expressing the Australian collective sense of sympathy to and solidarity with France. Figure 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 2.a), such as the interactive advertising in public spaces, allowing the audience sufficient space to gather and watch an event.
- *Artistic* (Figure 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 2.c and 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 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 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 2.g and 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**)

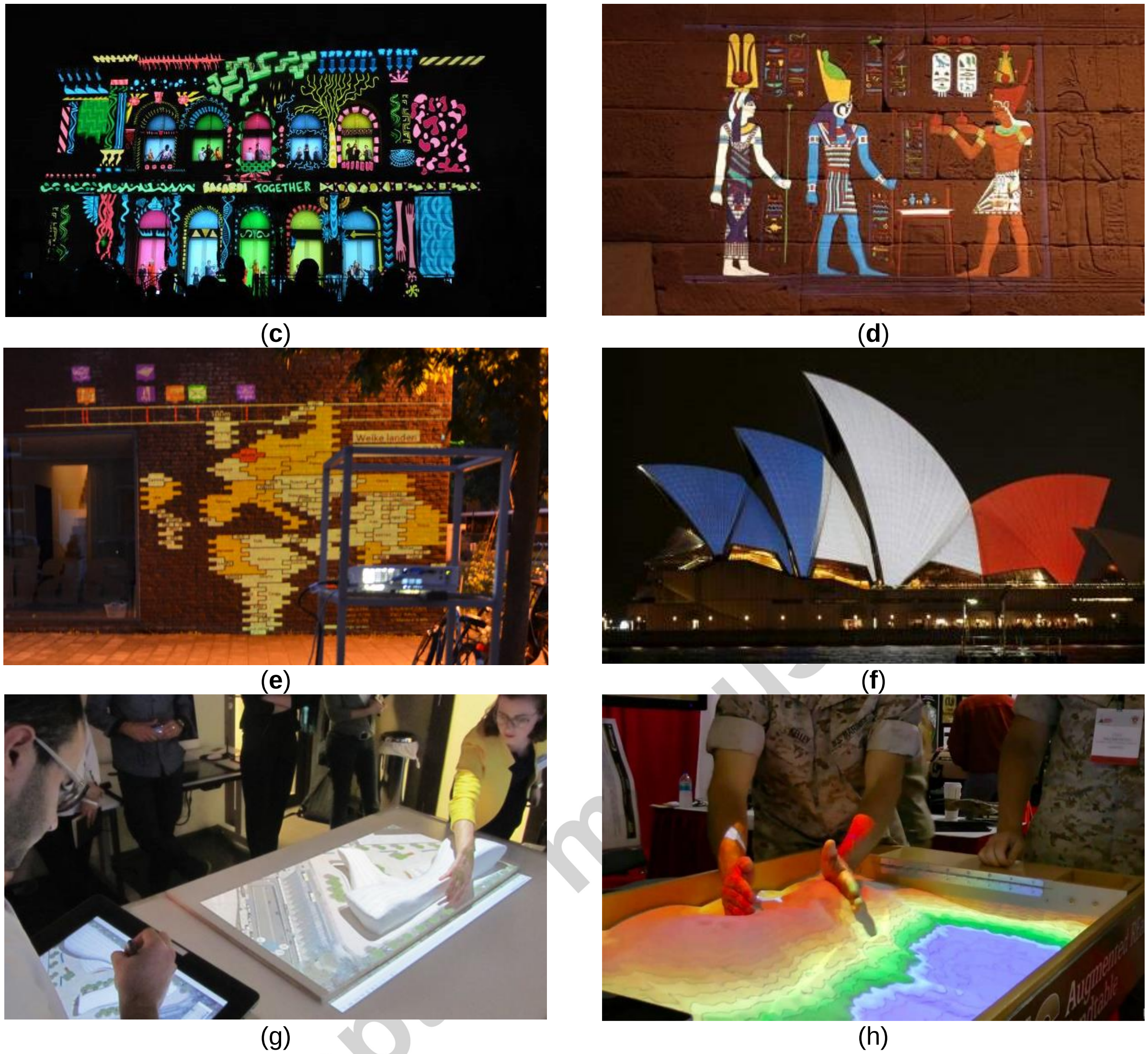


Figure 2. Different purposes of interactive and in-situ projection mapping: (**a**) commercial: advertising of BMW onto two buildings of Sun Tec City in Singapore (coloribus.com), (**b**) artistic: showing synchronized animations on existing urban elements during the festival 'Fête des Lumières' in Lyon (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?

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 3).

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

Figure 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, 232-234]. Digital reconstructions illustrate each phase [Massart, 2014]:

- *Ca. 1120* (Figure 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 4.2): an aisle is added at the northern flank of the nave, providing more space.
- *Second half of the 13th century* (Figure 3.3): 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 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 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 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 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 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 3).

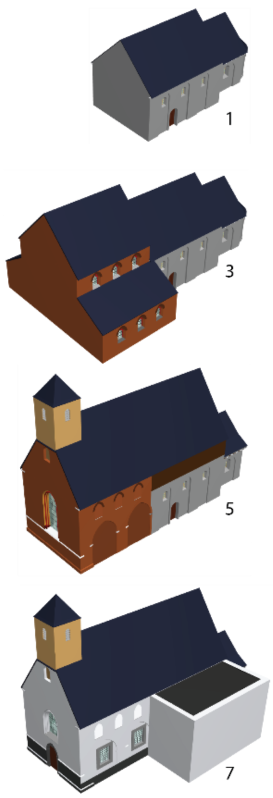


Figure 4. 3D models of the different building phases of Graethem chapel: (**1**) ca. 1120, (**2**) ca. 1230-45, (**3**) second half of the 13th century, (**4**) ca. 1500, (**5**) ca. 1658, (**6**) ca. 1720, (**7**) 19th century, (**8**) 20th century [Massart, 2014].

3. Design and development

3.1. Conceptual design

As illustrated in Figure 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 6, the projection content switches to show the particular interior simulation of the time period that corresponds to that physical model. 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 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 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 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.

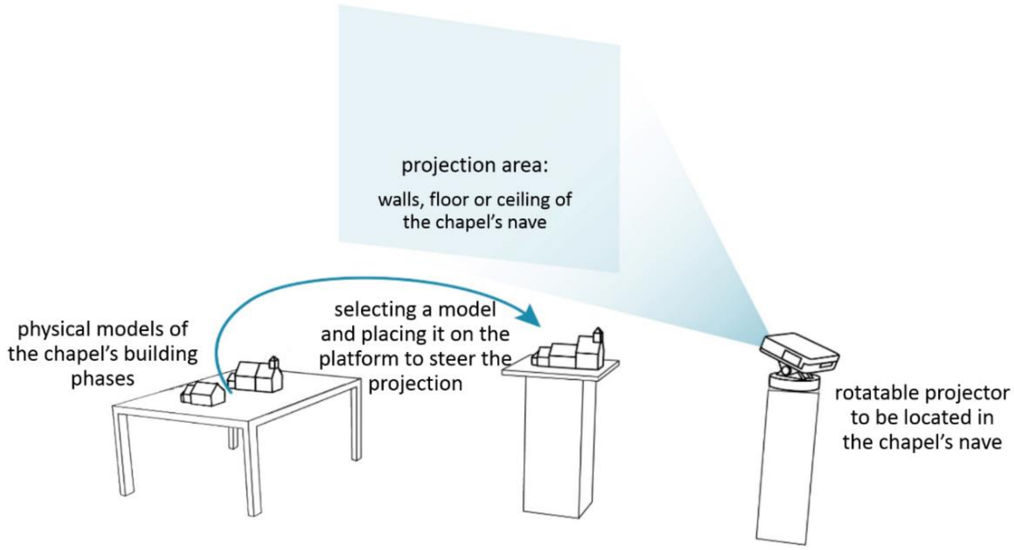
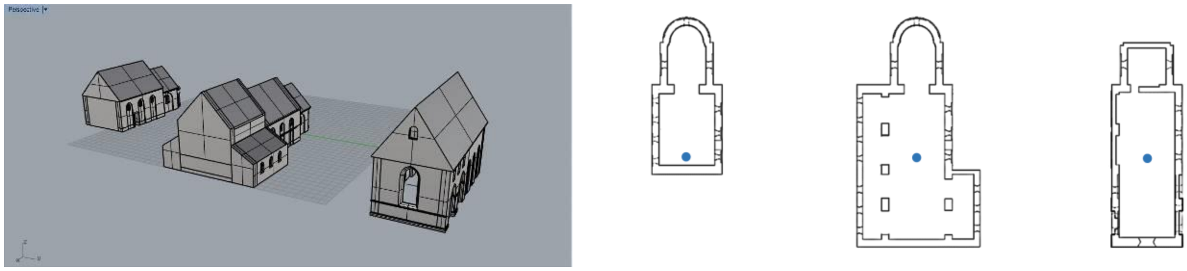


Figure 5. Conceptual design of the installation: rotatable projector steered by a tangible user interface (physical models of the chapel's building phases that visitors pick up and place them on the designated platform).

Figure 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).

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 7).

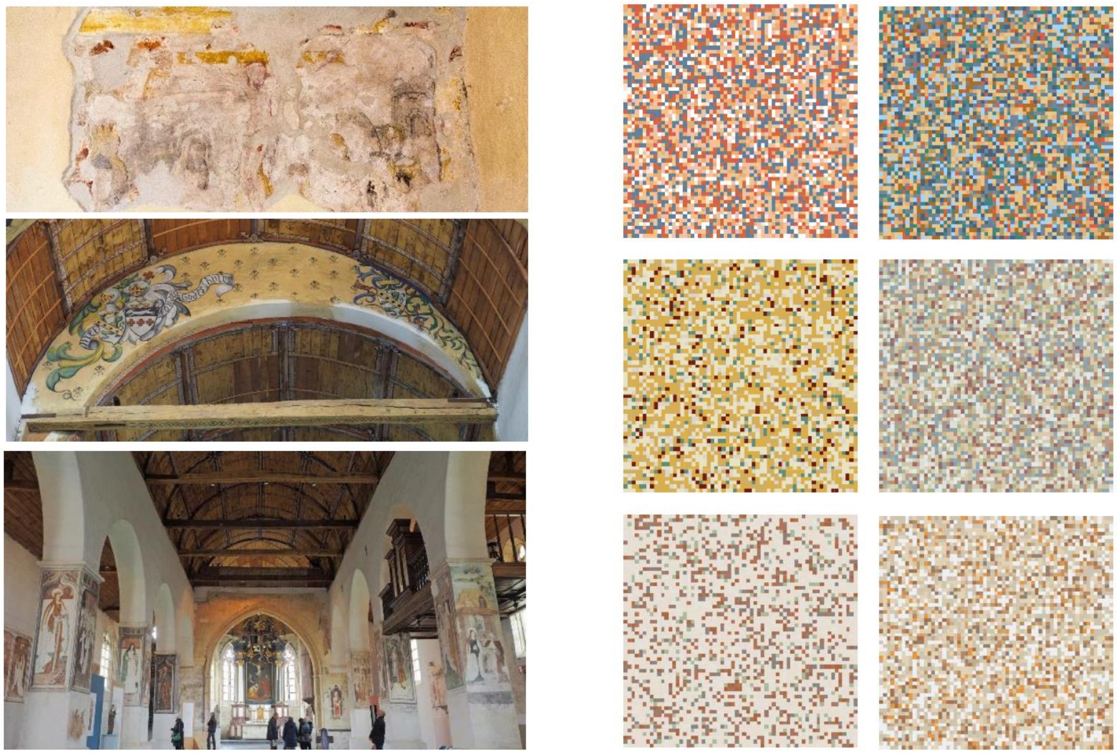


(**a**) (**b**)

Figure 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 8.a [Coomans and Bergmans, 2008]. This church and its paintings are part of the World Heritage nomination of 1998. As indicated in Figure 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.

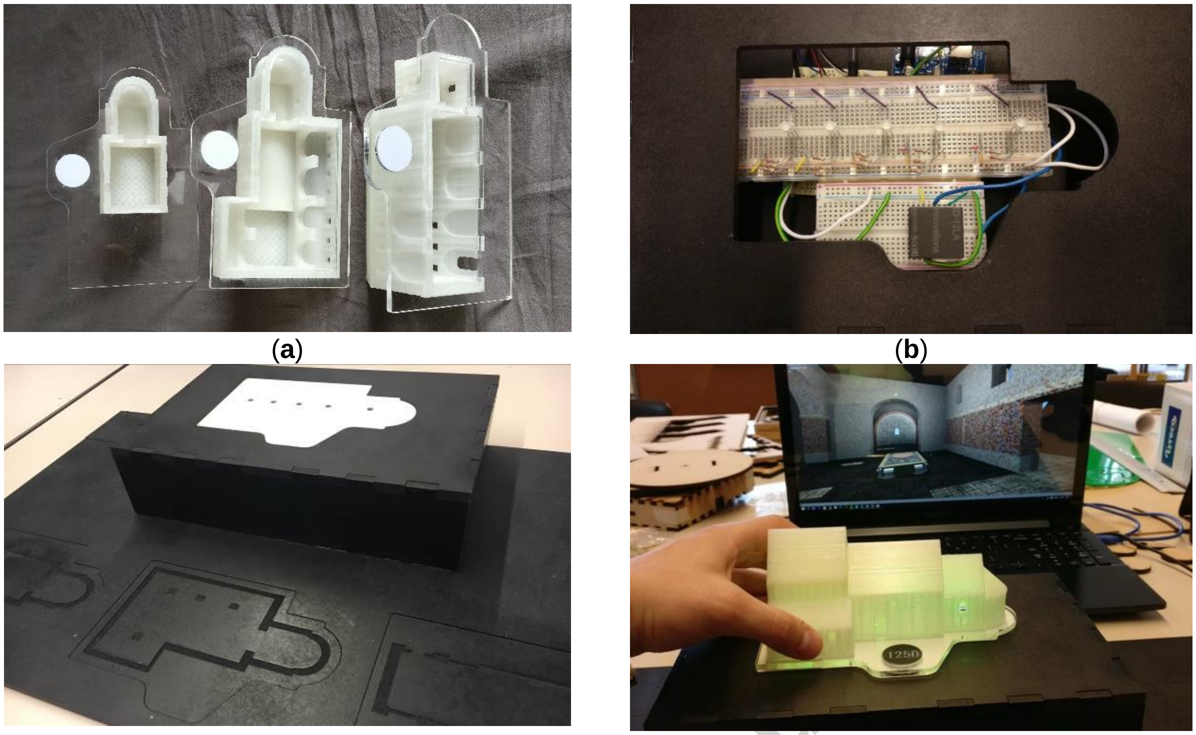


(**a**) (**b**)

Figure 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.

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 9.d). In addition, each model was purposefully hollowed out to allow users to examine and touch both its inside and outside characteristics (Figure 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 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 9.c).



(a) (b)

(c) (d)

Figure 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.

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.

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.

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.

4.12. 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.

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.

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.

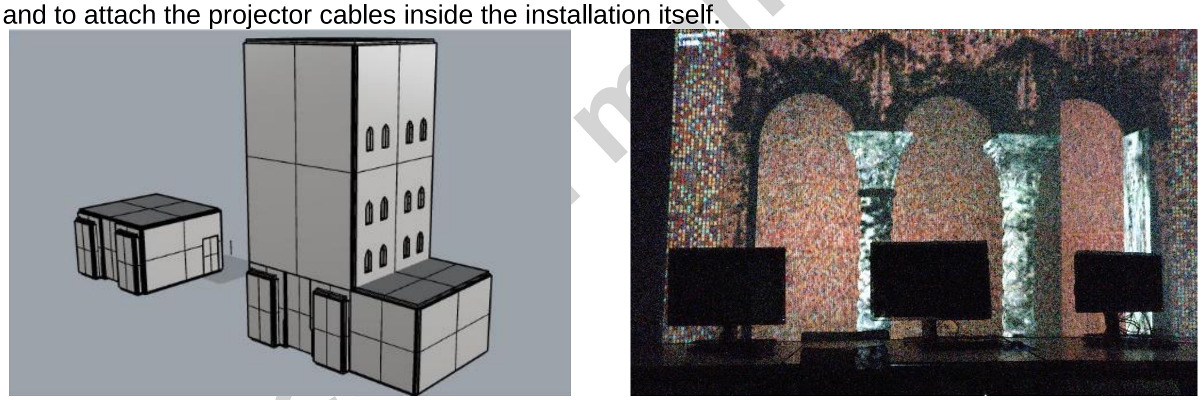
4.2.1. Lab study

A low-fidelity prototype was designed and implemented at the lab, consisting of a smaller projector that demonstrated the conceptual approach (Figure 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 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 11.a) to be tested through projection in the lab (Figure 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 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.

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

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. 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.

5.1. Comprehension of the spatiotemporal transformation of the chapel

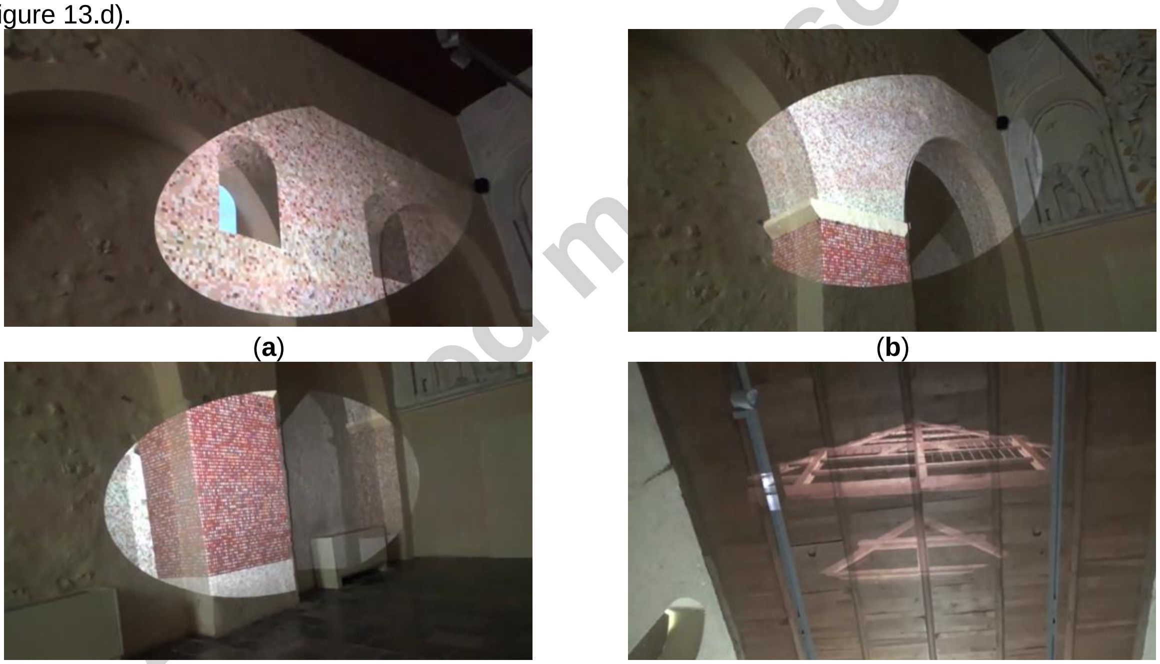
The results reveal that manipulating the physical models and rotating the projector at the same time allowed visitors to acquire spatial information about the chapel over time. They were able to report on the spatiotemporal transformation in a chronological order from the 12^{th}-century model to the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

For the 12^{th}-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 12^{th}-century model (Figure 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 13^{th}-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 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 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 13.d).



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

Figure 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 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 14.b), 7 participants drew a line to indicate the lower ceiling height (Figure 14.c), and only 2 participants sketched the windows of the apse (Figure 14.d).

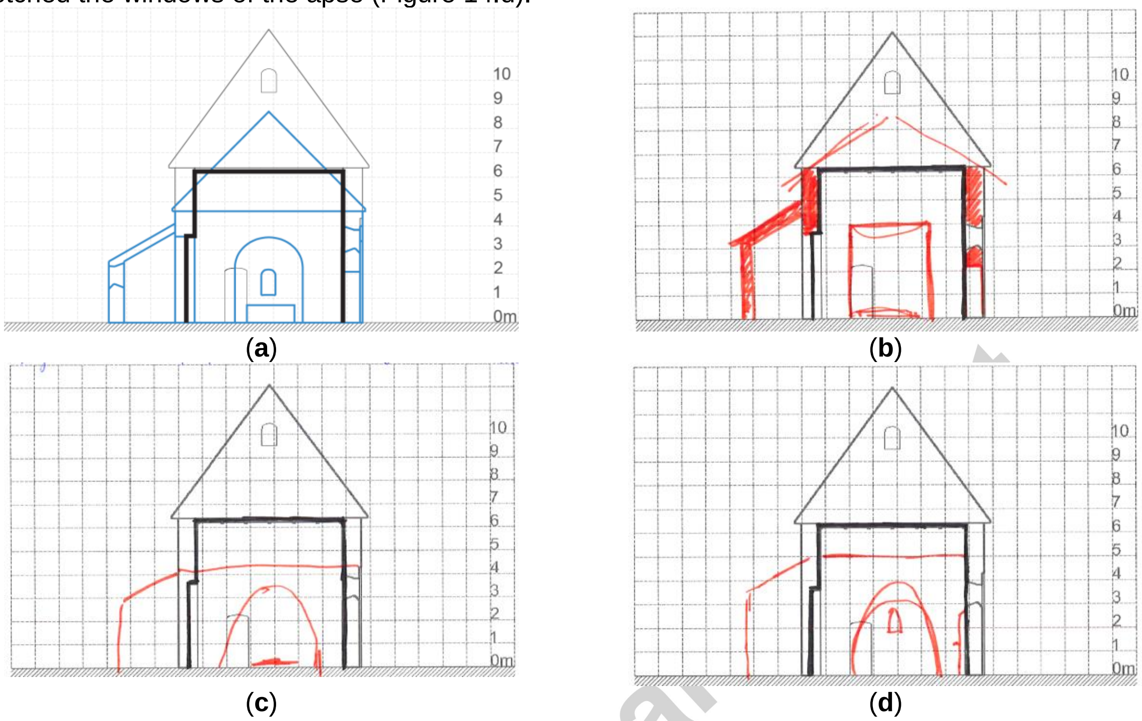


Figure 14. Sketching a cross section of the 13th-century model on a grid paper; (a) the correct section (in blue) compiled with a cross section of the current state of the chapel (in black), (b) sample of sketching the northern aisles and the opening to connect the nave to the choir (participant 6), (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 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 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]	
12th-century model	Lower and shorter space	14	*100 %*
(Ca. 1120)	Connection with choir and apse	8	*57 %*
	Door in southern wall	4	*29 %*
	Windows in the northern wall	2	*14 %*
13th-century model	Extension of archways and aisles	13	*93 %*
(Ca. 1250)	Colorful wall paintings	11	*79 %*
	Higher ceiling in the west side	10	*71 %*
	Small windows on the outer walls of the aisles	7	*50 %*
20th-century model	Higher ceiling in the east side of the nave	8	*57 %*

(1974)	Hidden wood truss structure of the roof	6	*43 %*
	Disappearance of the apse	2	*14 %*

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

5.2. User engagement

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

5.2.1. 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 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 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 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.

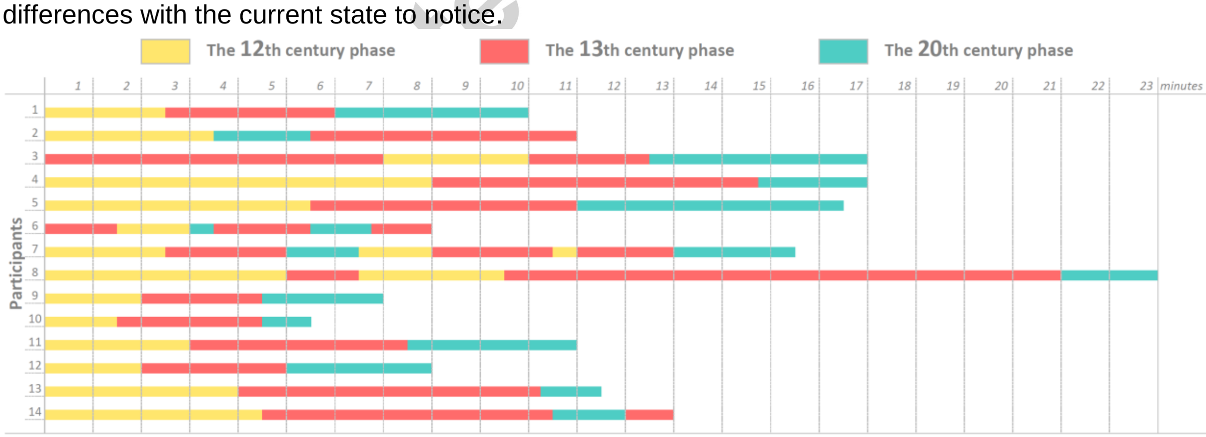


Figure 15. Chronological analysis of participants' interaction.

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.

5.2.2. 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 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].

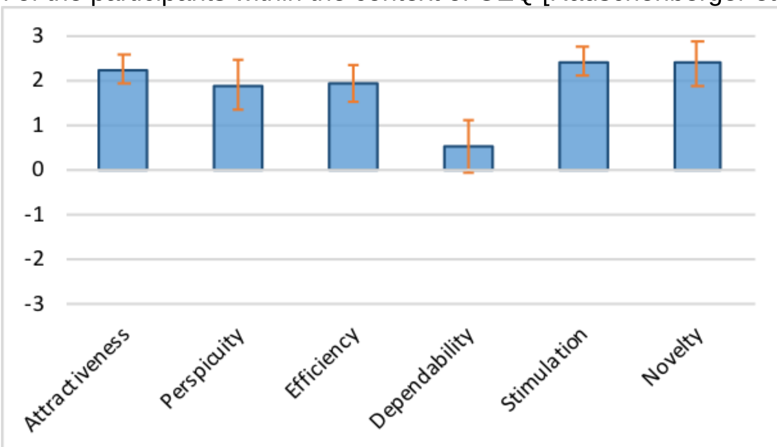


Figure 16. Results of the six scales of the UEQ (the error bars represent the 95% confidence intervals of the scale mean).

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.

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 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 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 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.

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 13^{th}-century model, and the connection with choir and apse in the 12^{th}-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.

6.3. Interactive projection mapping supports social interaction among visitors

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 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.

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 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 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].

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.

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.

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