AND THERE WAS LIGHT
PROJECTION MAPPING FOR HISTORIC PRESERVATION

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Chapter 1
Introduction

1.1 Abstract

Projection mapping is a technology that allows us to visually create the environment without physically altering it. Although it has been widely employed in the entertainment sector, its use in the field of cultural heritage preservation has been limited. With no physical contact and complete reversibility, this technology should be more widely used in the preservation field. Despite a few precedent cases, it was confined to large institutions. As the technology has become increasingly accessible, it allows small and underfunded institutions, such as house museums, to employ it. Physical restoration can be expensive, or sometimes impossible, and beyond the means of smaller institutions. As an interpretative tool, it enables these places to present their various histories, attract visitors, and provide interpretation in an innovative way. Its non-destructive and reversible manner distinguishes it from physical interpretation, which may require the removal or additions of materials. This allows us to temporarily and visually change the space into different time periods without requiring physical intervention allowing the space to remain in its current condition as a living document. Projection mapping has enormous potential but it is a little known technology. To begin promoting projection mapping, variables will need to be considered such as cost, size, calibration, and space limitations. The challenge of how to incorporate new technology without disrupting the historical environment as well as its implementation and maintenance need to be considered. These are issues that must be acknowledged before we can fully include this technology into our toolkit. This thesis attempts to establish a guideline to begin the use of this technology that is beneficial to the preservation of cultural assets and can be extensively adopted. It involves literature research, case study analysis, experiments and evaluation. This guideline attempts to clarify the processes of incorporating it into our interpretative toolboxes and advancing the discipline of preservation.

1.2 Rationale

1. Projection mapping has been successfully adopted in many industries including entertainment, medical, and manufacturing. It has been used for a few cultural heritage projects as a preservation tool. However, its focus was on cultural and artistic artifacts like sculptures and paintings. Thus, its employment for architectural preservation, to date, has been very limited.

2. Although there were a number of projects that used this technique in architectural scale, its use was almost purely artistic. There were a scant number of preservation
projects using this technology to restore the original appearance of the architecture, but it was restricted to large and well-funded institutions. As the software and hardware become more and more accessible, there could be a way to incorporate this technology into small and underfunded projects and institutions.

3. Physical restoration can be costly, sometimes impossible, and beyond reach for smaller organizations. Projection mapping has a potential to fill this role when traditional approaches are not viable.

4. With the non-destructive and reversible nature of projection mapping, it has a big potential for the preservation field. Some scenarios, in which sensitive surfaces or uncertain information need to be dealt with, can benefit from this kind of technology.

5. Projection mapping has potential to be used as a powerful tool for the interpretation of historic sites, however, it is largely unknown to the field of historic preservation. The capabilities and limitations for its uses in historic sites need to be analyzed and evaluated.

6. This sort of technology, like any other employed to preserve cultural heritage, is not objective; it has an influence on the information conveyed and how the public understands it. To begin incorporating this into our toolboxes, projection mapping must be assessed for its impact, efficiency, and authenticity.

1.3 Research Goals

1. This thesis aims to raise practical, and philosophical questions about the use of projection mapping in the historic preservation field, so that the technology becomes a topic of conversation among specialists in order to adopt it into our toolboxes and advance our field.

2. The research aims to test projection mapping capabilities and limitations for the use as an interpretive tool in the historic preservation field.

3. The outcome of this thesis will be a guideline for small historic house museums or other small and underfunded cultural institutions to use projection mapping as part of their interpretive tools to tell the stories of their site, attract tourists, and give interpretation to the general public in a novel and exciting way.

1.4 Research Questions

1. How might projection mapping be incorporated into the historic preservation field as an interpretive tool?

2. How effective is this technique for the preservation field? What are its capabilities and limitations?

3. Does projection mapping provide the potential to make significant contributions to the interpretation of historic sites?

4. The use of digital media in historic settings can help visitors learn more about the site, however its appearance in the historical environment is largely uninvestigated. Because of this reason, how might projection mapping be integrated into the
historical environment of house museums without disrupting its value? What is the impact or perception of the content and the heritage site?

5. With the advent of new technologies, it does not mean that the traditional way of interpretation should be abandoned completely. This thesis will explore an interconnected and complementary relationship of projection mapping with conventional interpretation.

6. What new understandings of the site can be brought by the relationship between digital and physical?

7. How does projection mapping relate to authenticity?

1.7 Methodology

The method for this research will involve both theoretical and experimental approaches. These two methods will complement each other to produce a comprehensive and practical framework for the use of projection mapping. The theoretical approach involved researching journals, books, articles, tutorials, and documentaries. Additionally two museums which have projection mapping as a permanent part of their exhibition were visited for research and to analyze findings. Information from this research will inform the experimental research which was implemented as both off-site and on-site experiments. These two approaches are synthesized to produce a framework for the use of projection mapping as an interpretive tool. Both approaches are applied to these four phases.

1.7.1 Literature Review

Extensive research was conducted on existing literature about projection mapping, light science, interpretation, and the use of digital media in museums and cultural heritage sites. This research was done to identify existing knowledge about projection mapping and relevant areas of this thesis in published literature. The literature consulted were scholar journals, articles, and books, as well as non-scholar tutorials and blogs online. The aim was also to understand every aspect of projection mapping and define gaps in the bodies of knowledge. During the research, four precedent cases that utilized projection mapping as their interpretive tool in cultural artifacts and sites were examined in detail. These cases were then analyzed in the next phases to generate findings of its use in the real world which would inform the guideline.

1.7.2 Precedent Cases

The extensive literature review showed a number of projects utilizing projection mapping for cultural heritage. However, four were selected because of their difference yet interrelated purpose of interpretation. The same areas of analysis were conducted throughout these projects which included visualization, presentation, content, accuracy and authenticity, workflow, hardware and maintenance, and feedback. The information was collected from primary and secondary sources as well as site visits where possible. The first project was the Temple of Dendur with data from scholar papers, articles, interviews with people involved in the project, and site visits at the Met. Rothko's Harvard murals, the second project, was analyzed through journals, articles, and an interview. The third project, Sant Climent de Taull, was determined through online publications, scholarly papers, and online documentaries. The last project was Thomas Cole National Historic Site which was identified through interviews, site visit, online articles, and annual reports.

1.7.3 Off-site and On-site Experiments
Findings from literature review and precedent cases analysis were gathered to design two off-site experiments. These hands-on implementations were conducted to test the capacity and limitations of the technique. The first experiment tested its effects on a similar color from different sets of artists’ pigment and binder. The second experiment was to test the capacity and limitations of the technique on values and chromas of the colors.

Moreover, to establish a guideline for the use of projection mapping for small institutes, an on-site experiment was conducted in the Vail House at Historic Speedwell, New Jersey which is a small house museum. The experiment aimed to restore the original faux sandstone masonry painting underneath a top layer of modern paint.

These experiments were conducted with an Optoma GT1090HDR, short throw laser projector. The software used were Adobe Photoshop and Resolume Arena.

1.7.4 Evaluation and Framework

The on-site application was evaluated through interviews with experts in the preservation field. This evaluation was designed to gauge the effectiveness of projection mapping in helping the visitors learn more about the site and also perspectives from the experts in terms of operation and maintenance. Interviews were done with preservation experts from the Morris County Park Service and staff from the Vail House.

Lastly, the framework for the use of projection mapping as an interpretive tool proposed by this thesis was developed according to the findings from the previous stages. Further areas of research were defined together with this part.
Chapter 2
Projection Mapping

Projection mapping has various titles such as video mapping and spatial augmented reality. For this thesis, the term projection mapping will be used. It is a relatively new technology that was introduced in the 1990s. This technique allows for the transform of the physical environment visually without the need of actual intervention through the use of light from one or more projectors. Its non-destructive and reversible nature separates it from physical conventional interpretations of a historic place which may require the removal of the historic fabric. Since equipment for projection mapping has become accessible for the public, this technique has been democratized and employed widely. The entertainment industry is one of the main users of projection mapping as can be seen in many events and concerts. The manufacturing and medical fields have started to incorporate this technique as well.¹

Projection mapping is still largely unknown and relatively new to the preservation field. This section discusses its history and theory, general and technical procedure, and its use in the historic preservation field. A better understanding of these characteristics of projection mapping will clarify unknown areas of the technology and establish a framework for its interpretation in the field.

Theorizing Projection Mapping

The fundamental concept of projection mapping is the use of projected light on surfaces which have more or less geometry corresponding with the image being projected. Among its multiple titles, it was under spatial augmented reality (SAR) that the technique was theorized. This taxonomy was defined as a part of augmented reality (AR) which was first defined by Milgram et al in 1994.² Under the reality-virtuality continuum, AR leans towards the real environment since its main objective is to inlay artificial contents onto the real physical surroundings and not to immerse people in a solely synthetic realm.³ (Fig 2.2) For this particular reason, it is the physical world that plays a vital role in this technique rather than the digital contents being projected. As a subcategory of AR, SAR differentiates itself mainly by the tools for display. In AR, users are required to utilize hand-held or head-mounted goggles in order to see the real world with augmented contents. However, SAR allows users to be immersed in augmented reality without wearing hardware which gives an ergonomic advantage. The only downside is that it is not mobile like AR.⁴ As a result, with all its advantages, SAR or projection mapping has become a prevalent method

for virtual reality display, dominating a long legacy of head-mounted displays, such as goggles and hand-held devices, in the industry.\(^5\)

![Diagram showing the components of projection mapping](Image: Preme Chaiyatham)

**Fig 2.1: A diagram showing the components of projection mapping**

To further categorize the technique, projection mapping, according to Bimber and Raskar, can be divided into two subcategories: surround screen displays and embedded screen displays.\(^6\) Each type can utilize front or back projection, depending on the location of the projectors in relation to the screen which can be either opaque or translucent. The first category immerses users in a real environment mapped with contents from multiple projectors onto multiple screens.\(^7\) There are a few notable past projects employing this type of display, but a more recent work is the Immersive Van Gogh Exhibit New York in 2021.\(^8\)

The second category, the embedded screen displays, employs one to a few screens to map content in a physical environment. It has less immersive experience but offers interactive advantages. Currently, horizontal and vertical display screens are the main types in the industry. For example, projection used in classrooms or meeting rooms is a part of this type of display. This type of projection mapping has been extensively used in many fields including preservation. Several cultural heritage projects fall into this category; a few of which are presented as case studies in chapter 3.

To conclude, the basic components of projection mapping can be categorized into three elements: hardware and software, content, and projected surface. The following sections in this chapter will closely examine the hardware and software. Chapter 3 and 4 will analyze the content and projected surface through precedent applications and off-site experiments respectively. However, to understand them in the contemporary context, its history and development need to be analyzed.

**History of Projection Mapping**

Projection mapping is a relatively new concept. Despite general agreement that the first project utilizing the technique was done around the 1980s, there was evidence that the

\(^{5}\) Ibid, 39.
\(^{6}\) Raskar, Welch, and Fuchs, “Spatial Augmented Reality.”
\(^{7}\) Ibid.
first documented work was, in fact, done in 1969. This work was the opening of the Haunted Mansion ride in Disneyland, which was the first projection on non-flat surfaces. The next instance was found more than a decade later. Michael Naimark utilized the technique in his immersive film installation Displacement in 1980. He was also the first one to coin the technique as “spatial correspondence” in the motion picture industry. Disney renewed their work with projection mapping in 1991, resulting in a patent called Apparatus and Method for Projection upon a Three-Dimensional Object, which effectively outlines a method for digitally mapping an image onto “a contoured, three-dimensional object.” This patent was followed by another from General Electric in 1997 entitled “Projection of images of computer models in three dimensional space.”

The concept of projection mapping was quickly developed as part of virtual reality as classified in 1994 by Milgram and Kishino. They were the first to classify a taxonomic framework distinguishing different types of mixed reality based on display methods which arranged research for different disciplines for a more organized structure. They further proposed the Virtuality Continuum to classify the level of reality and virtuality in which projection mapping was described as leaning toward augmented reality. (Fig 2.2)

![Reality-Virtuality Continuum](image)

Fig 2.2: Reality-Virtuality Continuum. Image: Milgram et al.

Later in 1998, Raskar introduced the term “spatial augmented reality” where the virtual object was projected to the physical world. It was around the turn of the twenty-first century that projection mapping was significantly developed. Many major projects were accomplished around this time pushing the boundaries and shaping today’s concept of the technique. Raskar et al. developed The Office of The Future in 1998, where projection

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9 Brett R. Jones, “Content Creation For Seamless Augmented Experiences With Projection Mapping” (Urbana-Champaign, University of Illinois at Urbana-Champaign, 2015), 7.
mapping could be utilized for any surfaces for tele-conferencing and visualization.\textsuperscript{16} \textit{KidsRoom} in 1999 by Bobick was another project using the technique to render a room to educate and entertain.\textsuperscript{17} With the emergence of projects using projection mapping during this time period, it was Raskar, in 2001, who came up with the mathematical principle allowing the technique to be more accurate on any surface using compensating color and geometry.\textsuperscript{18}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{image.png}
\caption{A conceptual drawing of The Office of the Future, 1998. Image: Raskar et al.}
\end{figure}

After the technology was made accessible for the public in the early 2000s, scientific theory and technical implementation were analyzed and distributed for non-expert uses.\textsuperscript{19} In 2005, Bimber and Raskar published a book on spatial augmented reality which established a foundation of the theory and implementation of the technique. Although their work was aimed toward laypeople, the mathematical formula and implementation were difficult to follow and understand. Combined with early examples of the technique, although it provides a fundamental concept of the technique, one needs to consult with more recent works to keep up with the constantly updated technology. Donato Maniello offered a more contemporary guideline for projection mapping which covered hardware, software, and implementation for the technique.\textsuperscript{20} However, as technological advance evolves rapidly and tremendously each year, updated information about those aspects need to be clarified.

\begin{flushleft}
\textsuperscript{20} Donato Maniello, \textit{Augmented Reality in Public Spaces, Basic Techniques for Video Mapping}, 1st ed. (Brienza, Italy: Le Penseur, 2015).
\end{flushleft}
Development of Projection Mapping

Projection mapping has various technical challenges which emerged since its beginning. Major aspects of the problem are related to size, color accuracy, and deformed projected contents. This is mainly due to the arbitrary nature of the projected surface. Since, most of the time, the surface cannot be altered, the method and content of the projection need to be modified instead to achieve the desired appearance.

One of the first developed techniques was to expand the size of the content. An attempt to enlarge the size of projection mapping beyond a single frame had been done since the early 1990s. The CAVE project projected contents onto six walls in a room for an immersive experience of the visitors. In order to increase the resolution of large surfaces, research in early 2000 developed a tiled-display system where multiple projectors were used to create a larger screen. However, this early work could only solve the problem of overlapping and disconnected joints by physically adjusting the hardware. Since then, many researchers have created solutions to achieve a seamless tiled display. Nowadays, most projection mapping software have integrated a function called edge blending which allows multiple projectors to blend the content together creating an enlarged size of the projection.

The advancement of the technology recently allowed users to overcome the previously mentioned difficulties. Nowadays software has been developed to perform digital calibration for projection mapping. There are two categories: geometric and radiometric calibration. In the first calibration, the mapping is registered by different functions in accordance with the shape of the projected surface. The resulting contents are rectified to fit geometrically on the surface. Most of the projection mapping software nowadays includes a function called warping which allows the users to easily perform this type of calibration.

The radiometric calibration is done to compensate for the color of the surface to achieve the consistent and desired color across the image. This method is highly complicated since it is formulated with multiple mathematical methods which involve the object’s reflectance, environmental lighting, and spectral responses. Studies on this method enabled projection mapping to achieve more accurate colors on non-white surfaces.

25 Brett R. Jones, “Content Creation For Seamless Augmented Experiences With Projection Mapping” (Urbana-Champaign, University of Illinois at Urbana-Champaign, 2015), 9.
although it was done only on lighter colors.\(^27\) It is made more complex with the limitations of the projector itself which included brightness, contrast ratio, and color range. Moreover, the technological limits on darker colors and gloss finishes still need to be examined.\(^28\) There were a few projects that were successful in using compensating light to rectify the colors of artifacts which will be examined in detail in chapter 3.\(^29\)

To conclude, projection mapping development is not without challenges. Multiple solutions have been invented and studied using different and sophisticated methods. However, thanks to the various software available for end users today, most of these solutions, namely warping and edge blending, are readily available. However, there are still challenges that are not as easy to overcome. These include the radiometric calibration process. The challenge of darker and glossy projected surfaces is still not yet solved. These issues of projection mapping, despite not being solved by this thesis, will be explored in chapter 4. off-site experiments, to test its effects in order to inform the guidelines in the last chapter.

**Hardware and Software for Projection Mapping**

To understand how the technique works, it is necessary to understand the fundamental components of the hardware and software. These two elements work together to manipulate the projected contents. Because technology for both components has been developed rapidly throughout the years, it is impractical to discuss every detail of their features. However, there are some major points that are necessary to review for a successful project using this technique.

**Hardware**

Despite its evolving nature, there are some basic projector parameters that can be reviewed when selecting one for a project. While information differs according to source, three fundamental elements apply: lighting condition, throw ratio, and resolution. These elements should be taken into account in conjunction with site limits and projected content in order to produce not only the best quality but also the most feasible solution for the site.

The first criterion is the condition of the site's ambient illumination. Dark and dimly lit environments are optimal for projection mapping. However, ambient lighting cannot always be regulated. This limitation is directly tied to the projector's brightness. Occasionally referred to as luminosity, brightness is a critical characteristic for any projector. To begin selecting the suitable brightness for the project, the formula below might be utilized as a starting point.\(^30\)

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\[ AL = \frac{(A'K)}{\text{gain rate}} + Y \]

AL is the ansi-lumen of the projector
A is the area of the projected surface in square meters
K is a coefficient which is always equal to 40
Gain Rate is determined by how dark the surface is. (Very Dark: gain rate < 1, Light: gain rate = 1, Very Light: gain rate > 1)
Y is the amount of ambient light. (Y = 1000-2000 when the ambient light is less prominent, Y = 3000-4000 when the ambient light is average, and Y = 5000-6000 when the amount of light is high)

The second criterion is the space’s dimension in respect to the projected image, which is determined by the projector’s throw ratio. The throw ratio simply indicates the size of the projected image in relation to the distance between the projector and the surface. The majority of projectors have a throw ratio of 1.5:1, which means that the image will be approximately 1 foot wide for every 1.5 feet of distance.\(^\text{31}\) However, certain spaces may be insufficiently large for normal throw ratio. This issue can be resolved by utilizing short-throw projectors, which were recently created for usage in small settings. A typical short throw projector has a throw ratio of approximately 0.5:1. This means that the image will be approximately one foot wide for every half-foot of distance. Recently, ultra-short-throw projectors with a throw ratio of roughly 0.25:1 have been available. However, when used with non-flat surfaces, this type of projector can cast shadows from protruding elements. Additionally, this style of lens can be difficult to set up.\(^\text{32}\)

[Figure 2.4: a comparison between different throw ratios. Image: Preme Chaiyatham]

The final factor to consider is the projectors’ resolution. The resolution of the projector has an effect on the quality of the projected image. A projected image is made up of hundreds of tiny squares known as pixels. As the number of squares grows, the image becomes more detailed. It is recommended to utilize the highest resolution possible. However, it can be costly. While there are numerous resolutions available at the moment, the following are the most common. SVGA is 800 x 600 pixels, XGA is 1024 x 768 pixels, WXGA is 1280 x 800 pixels, WUXGA is 1920 x 1080 pixels, and 720p is 1280 x 720 pixels, 1080p is 1920 x 1080 pixels, and 4k or Ultra HD is 3840 x 2160 pixels.

\(^{31}\) Digital Pressworks, “How To Choose A Projector For House Projection Mapping.”
\(^{32}\) Roland Hamilton, Interview with a projector supplier representative, interview by Teerat Chaiyatham, Zoom meeting, December 9, 2021.
In conclusion, a variety of factors influence the specifications required of a projector used for projection mapping. However, another factor affecting hardware availability is the budget. The higher the quality of the aforementioned factors, the more expensive the corresponding hardware. With this in mind, it is prudent to evaluate the site limits and projected pictures. In some situations, some site alterations may be required, such as closing a curtain to manage the illumination, which may result in a different perspective of the site. The projected content is also critical in picking the projector. Less detailed images may not necessitate the greatest quality.

As complex as these issues are, numerous vendors now offer advisory services through their representatives. Many considerations such as ambient light, projected content and size, and the size of the room should be considered while selecting the most appropriate projector for the project. However, it is vital for the project team to grasp these fundamental hardware concepts.

Software

Like the projection mapping hardware, the software has evolved significantly over time. Additionally, several software developers release continual upgrades on a yearly basis. As a result, it is also impractical to discuss each function in detail, as the program may become obsolete in the future. Instead, by examining the workflows associated with projection mapping, a pattern of software usage can be deduced. There is no clearly defined standard for the software used for projection mapping, particularly when it comes to cultural heritage. The only procedure that has been disclosed is for projection mapping on public exteriors. However, this literature, in conjunction with precedent applications in the field of cultural heritage discussed in Chapter 3, classifies these software as either production or implementation.

The first type is used to create and edit projected content. Among them are Adobe Illustrator, Photoshop, After Effects, and Premiere Pro. Illustrators, animators, and artists use them to create shapes, colors, animated effects, and immersive soundtracks to be incorporated as contents in the projection mapping project.

The implementation software includes those used for projection mapping calibration. Continuing the discussion from the part on projection mapping development, calibration can be classified into two types: geometric and radiometric calibration. The initial calibration is a standard feature of the majority of projection mapping software. Because one of the primary goals of projection mapping is to properly match the content with the uneven geometry of the surface, the warping function is utilized to accomplish this. The content can be divided into a grid pattern using this function. The intersection of each grid line is referred to as a control point. Users can manipulate these points to align the content geometrically with the surface. (Fig 2.5) Apart from warping, the majority of these programs have a feature called edge blending. This enables the collaboration of two or more projectors to map a bigger surface with smooth edge blending. While each software package includes a variety of distinct features, warping and edge blending are commonly employed.

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33 Maniello, *Augmented Reality in Public Spaces, Basic Techniques for Video Mapping*.  
34 A comprehensive list of projection mapping software can be found on the Projection Mapping.org website, https://projection-mapping.org/software/. 

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Radiometric calibration is used to alter the content’s color. Although this can be accomplished manually by utilizing the user’s relative color perception, there is available software that assists in seeing the final color of the projected material. This type of software takes into account the surface’s spectral reflectance and the colored light’s spectral power distribution.\(^\text{35}\) Apart from the Harvard Mural project, which will be discussed in Chapter 3, no other project currently makes extensive use of color calibration.

By 2022, over 60 projection mapping software products are available on the market. These programs range in price from $20 to $2000, depending on the developer and the subscription type (monthly, yearly, or lifetime). The majority of software also includes a free demo version with limited functionality that allows consumers to evaluate the product before purchasing it. Certain softwares, such as Resolume Arena, contain a variety of technical functionalities because they were designed primarily for both VJing (light performance shows) and projection mapping, which can be intimidating to certain users. However, a number of software packages have been built specifically for the purpose of projection mapping, notably MadMapper and HeavyM. These applications include a streamlined interface and process, which contributes to their simplicity of use. Recently, applications such as DynaMapper have been developed for tablet use, with even more simple features to make them accessible to non-specialist users. Each software package includes similar features such as warping and color management. They are, however, continually evolving and unique in order to attract users. As a result, nearly every developer includes comprehensive tutorials on their website or on third-party channels such as YouTube and Vimeo. These instructions are simple to follow and enable even non-technical consumers to use this technology.

Projection Mapping for Historic Preservation

Cultural heritage fields appropriate, adapt, assimilate, and modify the digital technologies they embrace in a symbiotic relationship. As a result of technical improvement, these technologies have the potential to offer a spectrum of options that were not before anticipated.\(^{36}\) Projection mapping is among the technologies that were developed for other uses but has been appropriated and adapted for the use in the cultural heritage field. With its capabilities of visual effects, projection mapping has been slowly employed in cultural heritage sites in recent years. As seen in many iconic monuments, it has been used quite extensively but mostly on the exterior façade. This is because of its unique projection surface and iconic status of the buildings.\(^{37}\) Due to its visual advantage, it connects the visitors with the sites and environment better than traditional media found in cultural places.\(^{38}\) Because of these potentialities, guidelines were issued in some countries for the use of this technique to enhance its cultural activities or tourism, for example, a projection mapping guideline by the Japanese government in 2018.\(^{39}\) However, to date there is still no established guideline from any authoritative body in the United States.

Although the cultural heritage field has started to incorporate this technology, its uses have been primarily focused on art exhibition, with only about 35% that had contents related to the sites. In this historical-related employment, the applications tend to be temporary in forms of light festivals to supplement commemorative or historical events with contents related to history, architecture, folklore, and artifacts. Moreover, its uses were largely done with large-scale projects on large historic buildings. However, among these projects were medium-size projects which incorporated specific contents such as historical figures and life.\(^{40}\)

These projection mapping projects with direct involvement to the historical contents of the site are categorized as self-reflective, according to Paquin.\(^{41}\) This type of intervention uses projection mapping in order to enhance the heritage through the reconstruction of deteriorated parts, depiction of its evolution, and utilization as museographic tools. However, there were also the uses of this technology on heritage sites with content unrelated to the place. They have been categorized as transcending and artistic mediation. The first type includes those projections of mapping events that use heritage sites as a promotional tool for commercial or commemorative and historical purposes which relate to contents beyond the boundary of the sites. The latter takes inspiration from the sites for non-didactic artistic or event-driven purposes. For the preservation purpose, this research only focuses on self-reflective use.

This self-reflective use is seen as a form of heritage interpretation. To comprehend how this approach has been employed as an interpretive tool, it is necessary to analyze the notion of historic site interpretation. Additionally, its contemporary challenges must be assessed in order to be addressed and clarified in the thesis’s guidelines.


\(^{40}\) Hengyi Li and Hiromu Ito, “Comparative Analysis of Information Tendency and Application Features for Projection Mapping Technologies at Cultural Heritage Sites.”

\(^{41}\) Georgescu Paquin, “Heritage Mediation Through Projection Mapping.”
Projection Mapping as an Interpretive Tool and its Challenges

Interpretation is a key component of any historic site. Its definition for preservation has evolved overtime. One of the most important definitions of it was in a seminal work, *Interpreting Our Heritage*, by Freeman Tilden in 1957. To him, interpretation is not just information, but a revelation based on information. He saw it as “an educational activity which aims to reveal meaning and relationships through the use of original objects, by firsthand experience, and by illustrative media, rather than simply to communicate factual information.” Apart from Tilden, subsequent scholars in the field expanded its meaning with a shared foundation. The self-reflective use of projection mapping is considered to be a type of interpretation for historic sites as it enhances and communicates their meanings to the public. However, its uses as an interpretive tool for cultural sites were not without challenges, especially in smaller institutions.

Firstly, the principles of interpretation proposed by preservation scholars are meant to be utilized in historic sites in various scales. Interpretation in small institutions like house museums is however problematic. In recent years, multiple challenges have been signified by experts. One of these challenges is the disintegration of technology in house museums. Digital media has been extensively used in large cultural institutions, but that is still not the case for small cultural institutions. Under this situation, these institutions miss the opportunity and risk being left behind. As Butler stated, regarding the advancing technology, house museums have been perceived as “fussy, dusty, places.”

Despite the scarcity of technological employment in cultural heritage sites, the use of digital media in these sites has been extensively researched and discussed by many scholars. In recognition of the importance of digital technologies, one of the first formal advocates was ICOMOS which issued the Quebec Declaration on the Preservation of the Spirit of the Place in 2008. One distinct guidance was to incorporate digital technologies which could promote the variety and continuous renewal of documentation. A wide range of new and more polished digital technologies are being deployed by heritage professionals in order to boost the value of digital, virtual, and remote services for public audiences.

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Moreover, many cultural institutions utilized digital media as tools to support visitors’ learning in various systems such as multimedia.

However, the use of digital media in these venues signifies two problems: the incompatible link between media and the task, and the lack of understanding of its potential to change the direction of current practice.\(^{50}\) While the first originates from the inexperience with the technology, it also relates to an ingrained idea of separation between material and virtual world in which some experts believe to be a factor limiting the potential of the technologies.\(^{51}\) In other words, the media can be an actual installation or object instead of a layer of interpretation supplementing the site. The latter problem requires a more imaginative and insightful approach to technology and more communication between experts in related fields which leads to another challenge.

The second challenge is related to the communication between different parties to create a successful project. As a digital media, that situates itself on the virtuality-reality continuum proposed by Milgram (Figure 2.1), the use of projection mapping with cultural assets is considered to be a virtual heritage, the materialization of heritage through digital means.\(^{52}\) This visualization of the heritage in this virtual mode is crucial to the transmission of knowledge to the public which is the main goal of preservation. Two components are crucial to the success of virtual heritage, authenticity and realistic representation. On the one hand, the authentic and accurate contents are desired by heritage professionals, on the other hand, the photorealism of the visualization is a goal for technologists.\(^{53}\) To achieve these two goals, experts in each field need extensive communications and fundamental knowledge of each other’s practice.

Particularly, the notion of authenticity is important for the application of projection mapping for cultural heritage, as it is an “essential qualifying factor concerning values.”\(^{54}\) First described in the Venice Charter in 1964, authenticity of cultural heritage has been developed over time to allow stakeholders to make informed decisions on their sites.\(^{55}\) The notion of authenticity was fully recognized in the Nara Document on Authenticity in 1994. This document does not only introduce the value of craftsmanship to the western preservation philosophy, but it also acts as a foundation for the development of the Nara Grid of Authenticity to assist the preservation judgements on authenticity.\(^{56}\) The Nara Grid is based on article 13 of the Nara Document, which takes into account the aspects of sources including form and design, materials and substance, use and function, tradition, techniques, and workmanship, location and setting, and spirit and feeling; and the dimensions of cultural heritage being examined including artistic, historic, social, and scientific. It acts as a checklist to evaluate aspects and dimensions of authenticity of the built environment and how decisions may impact its authenticity.\(^{57}\) However, the Nara Grid was not designed to fully test


\(^{53}\) Roussou, “The Components of Engagement in Virtual Heritage Environments.”


\(^{57}\) Koenraad Van Balen, 45.
the authenticity of the use of technology such as projection mapping on cultural heritage sites. As a result, a framework evaluating cultural heritage dimensions for authenticity and use of mixed reality (MR) was developed.\textsuperscript{58} This framework combined the \textit{aspects} of the Nara Grid with the \textit{dimensions} of MR including design, interaction, and content. (Fig 2.6) As part of MR, the use of projection mapping in the interpretation of cultural heritage may be examined in this framework in order to determine if this technology provides a “faithful and true perception” of the site.\textsuperscript{59} Because authenticity is evaluated qualitatively, this framework does not give a definitive judgment of authenticity.\textsuperscript{60} Furthermore, the application of this framework requires a certain amount of subjectivity.\textsuperscript{61} This framework is used to evaluate the authenticity of case studies in chapter 3, on-site experiment in chapter 4, and will be a part of the guideline in chapter 5.

\begin{center}
\begin{tabular}{|l|l|}
\hline
Design & Digital \\
& Physical \\
Interaction & Navigation \\
& Flexibility \\
& Comfort \\
& Security and Safety \\
Content & Knowledge \\
& Information Organization \\
& Accuracy \\
\hline
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\textbf{Fig 2.6: Aspects of Mixed Reality}


\textsuperscript{58} Ramos, “Mixed Reality for Historic Preservation.”
\textsuperscript{59} Ramos, 70.
\textsuperscript{61} Ramos, “Mixed Reality for Historic Preservation,” 70.
Lastly, guidelines for the use of projection mapping as a tool for interpretation in the preservation field have not yet been established. Although a guideline for the use of multimedia in museums has been proposed, it was concerned with general media and did not specifically address projection mapping. Furthermore, frameworks for the use of digital media in small institutions and mixed reality for historic preservation have been established, but they were more concerned with the conceptual aspects of their applications. As King found in her research, using digital technology is not without challenges. There is a gap between how it works in theory and how it works in practice. Thus, a practical guideline that institutions could follow for the use of projection mapping is still needed.

Conclusion

Projection mapping is a relatively new technology that has seen significant advancements over the last few decades. Numerous technological obstacles have been surmounted since its inception. Today's hardware and software, particularly with the growth of technology, allow the success of projection mapping projects. Additionally, due to the technique's unique visual effect, it can assist in the interpretation of historic sites and be

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integrated into the preservation field in a novel way. However, there are still certain challenges to overcome. Due to technological constraints, its effect on dark surfaces is mainly unknown. Its inclusion in cultural heritage sites, particularly house museums, remains limited. Additionally, heritage professionals must educate themselves about the core ideas of this technology in order to be incorporated in their toolboxes. Finally, the absence of practical guidelines for its application as an interpretive tool complicates its integration into the field. These difficulties serve as the foundation for following chapters.
Chapter 3
Precedent Applications

Recent years have seen an upsurge in the self-reflective application of projection mapping with cultural heritage sites. Although the use of this technology in the preservation field is regarded insignificant in comparison to other industries, such as the entertainment business, several efforts established the foundation for the discipline.

Through four precedent uses, this chapter examines the various ways in which this technology has been employed as a reconstruction and interpretive tool. Each application began with an overview of the project in order to make sense of the overall process. The design process was then explored, along with a discussion of many topics such as visualization, presentation, content, accuracy and authenticity, workflow, hardware and maintenance, and feedback. The evaluation of authenticity and use derived from the Nara Document on Authenticity, introduced in chapter 2, was used to assess the use of projection mapping on this notion. Each application finished with main findings that would be integrated into the guideline in the following chapter.

1. Temple of Dendur

Figure 3.1.1: Temple of Dendur in the Metropolitan Museum of Art, New York City
Image: Preme Chaiyatham
Project Overview

The color reconstruction through projection mapping for the Temple of Dendur was a collaboration of MediaLab and the Department of Egyptian Art at the Metropolitan Museum of Art in 2013. The former Met MediaLab director in 2012, Don Undeen, came up with an idea to use projection mapping technique to present graffiti, an ancient practice paying homage to the site, on the temple. However, it could give a false impression for visitors encouraging vandalism in the museum. Staying on this idea, Diana Craig Patch, acting associate curator in charge in 2012-2013, proposed presenting the original colors of the temple. Coincidentally, in the fall of 2013, Matt Felsen and Maria Paula Saba, working as interns at the MediaLab, had the skill set to produce the projection mapping. At the same time, Erin Peters was a fellow at the Egyptian department studying on the Temple of Dendur's colors. With personnel capability and resources at the Met, the project called “Color the Temple” was set to restore the original polychromatic appearance of the building. The project took two years to complete “through rigorous research, prototyping, discussion, and iteration,” bringing more understanding about the aesthetic and cultural aspects of ancient Egypt to the public.

![Figure 3.1.2: Projection Mapping on the southern facade of the Temple of Dendur](Image: Preme Chaiyatham)

Management Team:
- Dr. Diana Patch, Curator of the Egyptian Department
- Don Undeen, Media Lab Manager
- Marco Castro Cosio, Media Lab Manager
- Diana Craig Patch, Acting Associate Curator
- Erin Peters, Chester Dale Fellow
- Matt Felsen, Media Lab Intern
- Maria Paula Saba, Media Lab Intern

Temple of Dendur History

The Temple of Dendur was initially built on an ancient location south of Aswan on the Nile’s West Bank, near the Egyptian-Sudan boundary. Because the Nile flooded every year, the Egyptian government sought to regulate the flow of water by constructing a series of

1 Erin Peters, Color the Temple, interview by Teerat Chaiyatham, Zoom Meeting, December 2, 2021.
2 Diana Craig Patch, Color the Temple, interview by Teerat Chaiyatham, Zoom Meeting, December 17, 2021.
dams. By the late 1920s, however, Dendur and the surrounding area were inundated for nine months of the year. To make the situation worse, the Egyptian government intended to build a new dam in the 1960s, which would have made the floods permanent.  

UNESCO launched a salvage mission to conserve Dendur, during which the temple was recorded and disassembled. In appreciation of their aid throughout the campaign, the Arab Republic of Egypt offered Dendur to the United States in 1965. Lyndon B. Johnson gave the Temple to the Met in 1967. It was restored in the Sackler Wing, since then, and reopened to the public on September 27, 1978.

The monochromatic appearance of antiquity is traditionally supported in the modern world, however, in actuality, it was polychromatic quality that was integrated in ancient sculpture and architecture. Today, many Egyptian artifacts, including Dendur, are without its original pigments, giving the false impression that it never had been used. In the recent decades, efforts to recover the character of polychromed ancient art have risen to the fore, as seen through exhibits, conferences, and conservation programs. Color the Temple stood out among these projects as it utilized a novel technique to reconstruct the colors through light. With aims to recreate the authentic polychromatic effect, augment visitors’ experience, and develop a prototype for the museum, the project was positively received by visitors, introducing it as a new interpretive tool for the museum.

Design Process

Since the final projection was meant to be utilized as a prototype for a tool to enhance Museum visitors’ experience of the temple, it was critical to choose a scene in excellent condition with identifiable characters in order to maximize the projection’s potential. The team finally concentrated on a single scene on the southern facade of the temple with well-preserved relief and glyphs. With such detail, they were able to separate distinct aspects in order to illustrate the narrative of the scene. The chosen site was also owing to projection mapping limitations, since it required to be on the southern side of the temple, where natural light was reduced.

Many sources were used in order to acquire the temple’s original colors. This includes an examination of the temple itself, as well as surveys of other temples and other artifacts from the Met’s holdings. The surface of this scene lost its color as a result of floods and sand-wind erosion, and it could not be visually tracked even with a method known as visible-induced luminescence imaging. Aylward M. Blackman, however, documented some of the visible paint in various locations on the Temple’s inner walls in 1906. Despite the fact

4 Ibid
8 Roberta Panzanelli, Eike D. Schmidt, and Kenneth Lapatin, 5.
10 Ibid, 190.
11 Ibid
12 Joshua Barone, “Temple of Dendur’s Lost Colors Brought to Life at the Met.”
that no paint was documented anywhere on the outside, the information on the inside gave
information for the colors in the scene.

Aside from Blackman’s survey, the team reviewed earlier twentieth-century surveys,
including the Napoleonic Description de l’Egypte, which includes the Temple of Isis at Phiale
and the Temple of Hathor at Dendera. They were repaired in order to show their original
paintwork. Because it was built during the same early Roman time as Dendur, the inner part
of the portico of the Temple of Hathor functioned as another significant source of color.
Other artifacts in the Met’s collection were also inspected, including a painted column
capital and Charles K. Wilkinson’s Seth Slaying a Serpent from Hibis’ Temple of Amun.
Conversations with Conservator Ann Heywood about her work on the capital revealed that
a white gesso was initially applied to the stone beneath the colorful images before paint,
similar to what is found on the Temple of Hathor at Dendera.13

Because of the data limitations, the virtual reconstruction of the original colors was
agreed to be hypothetical.14 Still, it provided a basic concept of what the Temple would have
been like in antiquity.15 Keeping the lack of data in mind, during the Roman period many
paints could have been done differently. According to Marsha Hill, a curator in the Met’s
Egyptian art department, the colors could have been covered with patterns, wax, or varnish
to make it look ornate. For this reason, many variations of the temple were generated in the
final digital visualization, including ones with and without the elaborate patterns found in
Egyptian antiquities. This method of interpretation assisted the talk and tour according to
Marco Castro Cosio, manager of the MediaLab.16

The first step for the projection mapping was to create a digital file of the scene. A
high-resolution and scaled photographic documentation of the scene was taken. The team
utilized Adobe Illustrator and Inkscape to produce a vector file instead of a pixel-based
graphic for the projection, which allowed them to enlarge the image without losing
resolution.17 They discovered that some of the carved lines were difficult to detect owing to
erosion, during the vectorizing process. As a result, they needed to compare the vectors,
previously published copies of the hieroglyphs, and figures on the stone itself since they had
direct access to the temple. This allowed them to synthesize the information and come up
with the final outline of the scene.

They then utilized openFrameworks and imported the svg (scalable vector graphics)
file to edit the outline, fill the shapes with color, and draw the shapes in the application
window. This program was used in conjunction with MadMapper, a projection mapping
software, to perfectly match the graphic being projected onto the uneven contour of the
stone surface. Syphon was used in the procedure to connect the two applications and make
them function in unison.18 At this point, the preliminary visualization was ready to be
projected on the temple. After this initial test, they found that the resolution and brightness
of the projector was crucial to the project which required them to use a higher quality
projector.

After the preliminary projection in October 2013 with plain colors, further research on
the original paints revealed that there could have been patterns in the scene’s backdrop. For

13 Ibid
14 Peters, Felsen, and Saba, “Experiencing Ancient Polychromy at the Metropolitan Museum of Art’s
Temple of Dendur,” 191.
16 Joshua Barone, “Temple of Dendur’s Lost Colors Brought to Life at the Met.”
17 Peters, Felsen, and Saba, “Experiencing Ancient Polychromy at the Metropolitan Museum of Art’s
Temple of Dendur,” 193.
18 Peters, Felsen, and Saba, 194.
This reason, an adjustment needed to be done to the digital file. Because vectorizing took a long time, they created the patterns this time using pixel-based graphics in Adobe Photoshop. They took a high definition picture of the temple wall and printed it full scale to practice projecting once the files were available. The final version was perfected on-site to ensure the color accuracy on the beige-hue of the sandstone.

The team went a step further, moving away from static graphics and into interactive mapping presentations. Moving images were made to emphasize elements and narrate the story of the scene (Pharaoh-like Emperor Caesar Augustus offering wine to the gods Hathor and Horus), using Adobe After Effect. Furthermore, it was a suitable method to explain how the Egyptian translated the three-dimensionality into two dimensional figures and help the presentation. SpaceBrew was used to integrate openFramework with an ipad in order to control the animation.

Finally, they put the system in place on-site to test it and make some adjustments. The beige tint of the sandstone wall, as well as the ambient lighting, had an impact on the color accuracy. They manually calibrated the colors until they achieved the desired effect. Peters presented the project to a number of audiences, including current and previous Met directors, a few times before the public opening to demonstrate that the tool provided an upgraded interpretation of the site to the audiences. The exhibition was finally opened to the public in 2015 during the evening extended hours of the museum so that visitors had optimal viewing of the digital photos.

Evaluation

Visualization

The project utilized on-the-market software like Adobe Illustrator and Photoshop to visualize the outline and fill in the colors of the figures in the scene. When the scene was digitized and colorized, they used MadMapper, another available software to the public, to precisely align the image onto the carved stone surface.

The physical canvas for the projection mapping for this project was the sandstone surface of the temple. Although from a distance, the surface seemed to be smooth and flat, on a closer look, there were irregularities along with gaps and cracks in several areas. For this reason, there were some areas that were not covered with the projection, including cracks and seams between the masonry. However, these irregularities did not affect the overall quality of the projection. In actuality, the rough surface of the sandstone augmented the photorealistic quality of the visualization since the projected light altered only the colors and not the texture of the stone. This made the projected area conform with the overall appearance of the temple.

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19 Felsen and Peters, "Color The Temple: Using Projected Light to Restore Color."
Presentation

The project, although initially was accompanied with in-person presentation and narration, is now played on reel with three different scenes without narration. Each scene was shown for about a minute. Even though there is no narration anymore, the visitor can still learn about the project and the polychromatic past of the temple through a short text nearby. While this type of presentation is not ideal, it is the best way to practice regarding the space constraint of the Sackler Wing. The space is used for many activities including exhibitions and events. It is also a reflective space for visitors. Furthermore, hardware for narration is difficult to maintain and use. For these reasons, the most practical way to explain this project is to use signage for visitors to read. However, this signage can impart more information about the original colors and the temple to augment the visitors’ understanding. Visitors are allowed to move freely to enjoy the projection. This makes the visitation easy and flexible for visitors.

Content

The content of the mapping is in the form of three different scenes depicting what the temple could have looked like. Each scene is played for about a minute before it is changed to the next. The first scene depicts the figures in colors which was a character consistent throughout the Augustan temple. The second scene develops from the first with added details and patterns. These details were used during the Augustan era but one can

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20 Diana Craig Patch, Color the Temple.
never prove if it was applied to Dendur or not. The last scene is similar to the second one but with white background. The projection, combined with the written signage, “makes people get the idea that this is an attempt to produce what probably was there and could have been there.” Although the project only imparts the idea of the polychromatic past of the temple without in-depth information, one can easily access the museum website to find out more about the temple and its history. Furthermore, the museum has regularly hosted weekends in Dendur which allows visitors to see the projection and inquire with the experts should they have any questions.

**Accuracy and Authenticity**

Because of the limitation of the data, the digital visualization could only be hypothetical until further research reveals more information. The colors represented in the project were common during the Augustan era. The patterns and details, as well as the white background, were what had been done during that time but there was no proof if they were applied in Dendur or not. However, the essence of the project was to make visitors get the idea of the colorful past and feel closer to the creators. In terms of accuracy of the projection mapping, the result was very satisfactory both in the color and geometry. An initial review before the project was launched to the public was made by the director and former director of the museum with positive feedback. The projection at the Met today in 2022, after seven years of its first launch, is of the highest quality. The outlines of the figures are mapped seamlessly to the carving of the stone. The colors, though digitally generated, are not perceived as artificial at all. Overall, projection mapping conveys the authentic perception of the temple as the original material is only visually altered in terms of its color in an objective way.

![Figure 3.1.4: The process of adding the patterns onto the scene.](https://www.metmuseum.org/blogs/digital-underground/2015/color-the-temple)

**Figure 3.1.4: The process of adding the patterns onto the scene.**


21 Diana Craig Patch.

22 Diana Craig Patch.
The projector was mounted on a higher level of a wall, away from the temple, in order to avoid interfering with the temple. The projected light is played on a reel during the opening hour. Visitors can only interact with this repeated reel. The projected content is accurately aligned to the geometry of the reliefs and each block of the masonry.

The sequence of projection mapping allows visitors to see the actual surface of the sandstone of the temple. Visitors can see original material of the temple when the projector is not projecting images. The projector used for this exhibition is a high-brightness model, ensuring that the colors are accurate even with the presence of daylight. The original colors were also accurately identified by extensive research.

The use of projected light is not destructive to the surface of the stone. The application allows the temple to continue its function as the main attraction of the wing. The projected light is easy to navigate as there are only three scenes to depict. It is also quite flexible as it is on reel during opening hours. The projected light enhances the function of the temple, transmitting the knowledge of its original colors to the public.

The application utilizes the non-permanent technique of projection mapping to depict three possibilities of the original color scheme. The location of the application depicts an important scene of the temple (Emperor Caesar Augustus offering wine to the gods Hathor and Horus)

Visitors can still experience the spirit of the place in other parts that are not projected. The projected light does not replace the whole temple as the main attraction. The visitors can interact with other portions of the temple without the projected light. The application is only in a small area. Although it gives the notion of the original polychromatic appearance of the temple, it still does not give the feeling of the colorful temple in its entirety.

Table 3.1: An evaluation of the cultural heritage dimensions for authenticity and use of projection mapping of the Temple of Dendur.

**Workflow**

The project provides a detailed workflow for projection mapping, when there is no immediate confirmation of the original colors to visualize. Due to the tight time frame, the research and visualization team needed to work in a parallel and collaborative manner. A hypothetical version was created first so that the visualization team could test out the technology. Details were added as they discovered more evidence through research.

The team also used common software that was comprehensible to lay people and easy to access. Figure 3.1.5 describes the workflow of this project.

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23 Erin Peters, Color the Temple.
Hardware and Maintenance

The Sackler Wing is a large-volume space with a transparent glazed wall to the north, allowing huge amounts of sunlight into the space. Furthermore, the distance between the temple and the closest wall for projector installation is quite far. For these reasons, a high-quality projector is required. The projector is attached to a wall to the south of the temple from the ceiling. To hold and conceal the projector, a custom-made platform was built to cover it. Although it was painted in the same color as the stone-cladded wall, the projector is quite conspicuous to visitors as it is the only element attached to the wall.

Although there is no data on the specification of the projector used in this project, the projector itself costs around $17,000. According to Dr. Diana Patch, Lila Acheson Curator in Charge at the Met, she indicated that the projector needs to be maintained regularly and replaced if needed. It needs to be replaced soon and the cost would be around $20,000.24 The replacement necessitates the purchase of a new model for the projector since the technology is constantly updated. Thus, the platform holding the projector, as well as the wiring system, need to be replaced to accommodate the new model as well.

Figure 3.1.6: The projector was placed conspicuously on the south wall of the Sackler Wing.

Image: Preme Chaiyatham

24 Diana Craig Patch, Color the Temple.
Feedback

Color the Temple has been well received by visitors since its debut as can be seen from positive comments online.\textsuperscript{26} However, the project was doubted at first by experts. The hypothetical nature of the visualization might have given false information to the public.\textsuperscript{26} Nevertheless, Color the Temple is successful in a sense that it was a prototype for a tool expanding visitors’ experience.\textsuperscript{27} It imparts the notion of the original polychromatic appearance of the temple to the public, adding a layer of interpretation to the structure. This projection mapping, initially exhibited for a short period of time in 2016, was brought back as part of a permanent exhibition which proved the success of the project. Patch believes in it enough that she recently upgraded the projector to be used in this exhibition for the next five years.

“One of the really important things about this is people think so much art architecture around the world is quite beige, clean, non-decorated style is what the world all aspired to, when in actuality, most of the world loved color. that is very important for that aesthetic that is sunk in the west of cleanness and calmness as what everybody should be doing, this really changed that. And I think that’s what shocked people when they saw Dendur. And I think that this helps people realize that aesthetics are different around the world and this helps you see what that cultural aesthetic is when preservation doesn’t allow you to.”\textsuperscript{28}

Findings

Color the Temple makes use of the reversibility of projection mapping. As a result, it can show not just one but numerous iterations of the temple’s possible color schemes. The project educates visitors about the vibrant appearance that occurs when restoration is impossible. The installation is accompanied by signage that provides information for visitors to comprehend what they are looking at, demonstrating that this type of interpretation does not require a narration for the visitor. However, more information should be provided to augment visitors’ understanding. Additionally, the project highlights the nature of this type of project’s workflow, which is that research and visualization may be undertaken concurrently, maximizing the process within a condensed time frame.

Additionally, it demonstrates that projection mapping may be used in the presence of uncontrolled ambient light by utilizing a high-brightness projector. However, this type of projector is more expensive than a regular model. Thus, the use of it in smaller institutions may still be restricted. In terms of geometry and color calibration, the project made use of readily accessible software. Although the availability of information merely covers the cost of the hardware, the project’s completion was made feasible by the presence of individuals capable of doing research and creating the projection mapping. As a result, the overall cost of this project was low in comparison to the case studies that will follow.

\textsuperscript{25} Felsen and Peters, “Color The Temple: Using Projected Light to Restore Color.”
\textsuperscript{26} Erin Peters, Color the Temple.
\textsuperscript{27} Ibid.
\textsuperscript{28} Diana Craig Patch, Color the Temple.
2. Mark Rothko's Harvard Murals

![Figure 3.2.1: Mark Rothko's Harvard Murals](Image: James K. Ufford and Michael Nedzweski. © President and Fellows of Harvard College (Harvard Art Museums))

**Project Overview**

From November 16, 2014 through July 26, 2015, the deteriorated Harvard murals by Mark Rothko were virtually and digitally restored, pixel by pixel, by the use of projected light from a digital projector, a novel technique used for the first time on paintings. The restoration was a work that required several years of research by a team of art historians, conservation scientists, and conservators from the Straus Center for Conservation and Technical Studies and the Center for the Technical Study of Modern Art at the Harvard Art Museums in collaboration with the MIT Media Lab's Camera Culture research. The project was a proposal, and the institutions hoped that it would spark active debate and discussion concerning the use of light-based technology as a conservation tool.

![Figure 3.2.2: Comparison of the original Murals (left) and the virtually restored version (right)](Ibid.)

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30 Ibid.
Mural History

Mark Rothko is regarded as one of the most important American painters of the period after World War II. He was a key figure in the abstract expressionist movement. Along with other well-known abstractionists of the period, he altered the way people interpret art. As a consequence of this trend, the art world's attention shifted from Paris to New York. By the 1940s, he had developed his characteristic style, which featured floating rectilinear patterns on a colorful backdrop. Throughout his career, he completed three mural projects, including the Seagram Murals, Harvard Murals, and the Rothko Chapel. These works attempted to create settings in which the spectator might immerse oneself.  

Mark Rothko designed these rooms filled with his paintings from the late 1950s to 1970. The Harvard University's commission started in 1960. The Murals were located on the tenth floor of the newly built Holyoke Center designed by José Lluis Sert, a modernist who was the dean of the Graduate School of Design at that time. The space was aimed to bring together the best of Modernism in that period. In 1963, the five Murals were exhibited in this space, before they were moved to the Solomon R. Guggenheim Museum in New York City. They were brought back in 1964 and shown there until 1979.  

Rothko sought to create works that would serve as a representation of a public space. The Murals worked together to create a sense of unity in the space. After more than a decade of exposure to natural sunlight, each Mural was drastically faded due to a pigment called Lithol Red. What was once a unity, these five paintings had all drifted off on their own. The deterioration was noticed early on, but because of the complicated ownership, no action was taken. As such, the original crimson red color was turned into a light blue hue with varied degrees of deterioration in relation to the location and distance from the windows. In 1979, the murals were removed from the public and kept in a dark storage.

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34 Ibid.
They have rarely been seen since then, except in 1988 when they were exhibited at Harvard University in the James Stirling designed galleries of the Arthur M. Sackler Museum. This exhibition proved a disparate experience from their original setting because of the architectural configuration of the space. Moreover, the murals were not included in Rothko’s Room, a documentary in 2000 which suggested that they could not retain its “critical discourse and public awareness” since its removal in 1979.35

**Design Process**

Since the beginning of the restoration, the conservators were faced with challenges of how to restore the faded paintings, which have an extremely delicate unvarnished surface. And they also needed to find a way to display the paintings to the best effect when the original room, the original environment, was no longer available.36 To gain a better understanding of the original appearance of the murals, the conservator team had studied sketches, unused canvases, photographs, and materials in both archive and treatment files.37

The conservators used data from three sources to determine the original colors: faded Ektachrome slides from 1964 that were digitally restored in collaboration with the Imaging and Media Lab at the University of Basel, Switzerland; a vintage color reference card; and direct color measurements taken from a sixth panel.38 The sixth panel was brought to Harvard in 1963, but it was not included in the final display. It was this last panel that provided key information for the original color reconstruction.

When it comes to the actual restoration, the idea of reversibility is of highest concern. According to CTSMA director, Carol Mancusi-Ungaro, the Harvard Murals could not be in-painted, manually compensating for the color loss, due to its fragile surfaces.39 Furthermore, the effect of matte and gloss finishes that Rothko achieved would be lost if they were to glaze it. The team had considered the use of augmented reality goggles, however, the technology at that time was not sophisticated enough.40 Thus, they considered the use of projected light for the restoration instead. Since human visual perception is a combination of the source of light and object surface, they chose to alter the light source to change the color of the surface.

The setup was similar to that by Grossberg in 2004 and Law in 2009.41 The restoration process could be divided into two categories, the geometric and radiometric compensation,

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36 Ibid.
38 Harvard Art Museums, “In a New Light.”
both using a software called MATLAB. High-definition photographs of the existing murals were taken to incorporate into the compensations. The first compensation ensured the geometric coordination between the projector, the camera and the target image. Because the canvases have been stretched multiple times since the reference images were taken in 1964, the four corners of each painting are no longer viable reference points. The target picture and the current photo were computed and registered using Matlab’s control point selection tool, which selected and correlated tiny characteristics such as paint drips in both photographs.

The radiometric calibration performed with the murals came from a study by Grossberg in 2004, which was processed in a custom-made software. Neutral gray light, equal red, green, and blue value, was projected onto the murals with different levels and was recorded. A calibration curve was created for each pixel of the recorded digital images, as well as for each of the red, green, and blue channels, describing the reflected light seen by the camera sensor as a function of the digital input values controlling the illuminating light level from the digital projector. The color mixing matrix was also considered since the color channels were not independent; for example, the green camera channel will respond to a change in the projector’s red channel. Compensation pictures were created using the three calibration curves and the color mixing matrix for the red, green, and blue channels. Each projector pixel’s red, green, and blue values generate the projecting light for the painting, ensuring that the reflected light seen by the visitor matches the intended unfaded appearance. A second geometric modification was performed using another software which utilized the Harris corner detector and RANSAC (RANdom SAmple) to guarantee that each pixel of the compensation picture illuminates the proper spot on the painting.

Following the calibrations, a smaller size prototype painting was made using the same pigment binding process and canvas support as the Rothko Murals. The mockup was then exposed for several weeks in certain regions with a 250 watt halogen tungsten bulb. As a consequence, there were fading patches with soft and sharp edges. This mockup was used by the team to test the system and develop the software. The compensation image, generated by the software using the radiometric calibration described, was projected onto this faded prototype. The test resulted in the disappearance of the sharp edges of the fading sections, as shown in Figure 3.2.3, and the correction was seamless.

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42 MathWorks’ MATLAB (acronym for “MATrix LABoratory”) is a proprietary multi-paradigm programming language and numeric computing environment. Matrix manipulation, charting of functions and data, implementation of algorithms, design of user interfaces, and connecting with programs written in other languages can be done with MATLAB.
Aside from these two calibrations, the lighting in the gallery had an important influence in seeing the murals. The conservation team had to spend a significant amount of time working on the ambient light within the gallery in order to regulate its influence on the murals. They put the system through tests on the fifth panel. Different color corrective light-to-ambient light ratios were evaluated. It was discovered that when there was no ambient light, the painting appeared as a bright rectangular light in the dark and was rejected as misleading. The ideal display settings were determined to be a 1:1 ratio with 25 lux from the projector and 25 lux from the extra halogen tungsten bulbs at 45 degrees. The combination of 50 lux was within a standard set by Thompson before the remaining red pigments were quantified as light sensitivity by a microfadometer. This lighting condition was applied to the actual venue of the exhibition where they needed to construct a space with the exact same size of the room in the Holyoke Center and block light from other parts of the gallery to really achieve the correct representation.

These calibrations resulted in a color-corrected “restoration” of the murals. An overall process is summarized in the diagram below. (Fig 3.2.4) An image of the painting in its present condition was captured by a high resolution camera. This image was compared to

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46 Ibid, 8.
the target image to perform the geometric and radiometric calibration in the software which resulted in a compensation image. The computed compensation image was projected onto the faded Mural, resulting in the appearance of the Murals if they had been restored.

![Image](image-url)

Figure 3.2.4: A diagram summarizing the process of the project

**Evaluation**

**Visualization**

The visualization process of this project was done by experts who knew the science behind this technology. Ramesh Raskar, along with other two students from MIT, developed a sophisticated custom-made software which calibrated the geometry of the compensating light to align with the actual murals pixel-by-pixel. Furthermore, the color calibration also used the complicated calculation of red, green, and blue light, resulting in compensation images of lost colors. The calculation included a large data set of two million pixels on each mural, as well as reflectance and ambient light, to ensure the quality.

The basis of the visualization of this project primarily relied on human color vision called ‘color constancy’[^49], which is our capacity to see colors as largely consistent under shifting lighting conditions. In other words, the projector threw the exact corrected color of light at the exact perfect position on the murals, causing it to reflect off the old, faded...

pigment and into the viewers' eyes, working with their tendency for color constancy and deceiving their brains into perceiving the original colors.

Even with these sophisticated calibrations that produced miniscule scale of corrective colors, there still were limitations. The projected images needed to be a bit defocused to eliminate the thin black outline of each pixel caused by the projector. Furthermore, the canvasses’ matte surfaces did not distribute light evenly. This interfered with the alignment of the projector and the paintings, particularly when seen from an angle.51

Presentation

The murals were exhibited in a gallery environment which tried to mimic the original location of the Murals designed by Rothko. The compensation colors were projected onto the murals all day from the opening of the gallery until 4 pm. The projectors were shut off around this time to let the visitors experience the deteriorated state of the murals. Moreover, the placement of the projectors and the Murals allowed visitors to block the projected light which enabled them to see the unlit version on demand.

Content

The content being projected onto the murals did not aim to be didactic. However, it transported the viewers back to the 1960s when the murals were first created. The unprojected state on the murals at 4 pm was when the viewers could experience the current state of the murals which allowed them to compare the two versions of them which emphasized the effects of the passage of time.

Accuracy and Authenticity

The accuracy of the color reconstruction came from a close collaboration between many parties. Experts on historic photo restoration worked to digitally reconstruct the fading Ektachrome slides from 1964. Together with access to the sixth panel, which was unfaded, they were able to achieve the original color of the murals.

However, it was not only the projected compensation colors that mattered. The ambient lighting of the gallery played a vital role in the color perception of the restored murals as well. Thus, because of the emphasis on color accuracy of the project, they also needed to calibrate the environment lighting in the space in order to achieve the desired effects that they wanted on the Murals. Because of these reasons, projection mapping applied to the Murals imparted the authenticity of the artworks. Visitors could view both the faded originals and the virtually restored versions.

<table>
<thead>
<tr>
<th>Form and Design</th>
<th>Design</th>
<th>Interaction</th>
<th>Content</th>
</tr>
</thead>
<tbody>
<tr>
<td>The murals were exhibited in a gallery environment which tried to mimic the original location of the Murals designed by Rothko.</td>
<td></td>
<td>n/a</td>
<td>The customized software enabled the geometric and color accuracy of the virtually restored Murals.</td>
</tr>
</tbody>
</table>

Lighting conditions were controlled to ensure the accuracy of the final appearance of the restored colors.

<table>
<thead>
<tr>
<th>Materials and Substance</th>
<th>The exhibition was designed to turn the projectors off at 4 pm everyday so that the visitors could see the original faded colors of the Murals.</th>
<th>Visitors could interact with the projected light, allowing them to see the Murals with and without the projected light at the same time.</th>
<th>The use of projected light retained the unique gloss and matte surface and also the brush strokes of the original Murals. The final restored colors were accurate due to extensive research and calibration by experts in the field.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Use and Function</td>
<td>Although the exhibition was designed to replicate the original setting that the Murals were installed, its use was only for viewing in a gallery setting.</td>
<td>The exhibition allowed the visitors to interact with the Murals in a setting replicated to look like the original.</td>
<td>The projected light enhanced the understanding of the Murals' original colors while preserving the deteriorated unlit originals.</td>
</tr>
<tr>
<td>Tradition, Techniques, and Workmanship</td>
<td>n/a</td>
<td>The virtual restoration of the Murals allowed visitors to experience the painting technique used by Rothko because it only visually changed the color.</td>
<td>The final projected light came from extensive research on Rothko’s Murals. As a result, the accuracy to preserve the painting technique was achieved.</td>
</tr>
<tr>
<td>Location and Setting</td>
<td>The setting was in a gallery replicating the original location of the Murals. However, the projectors were visually conspicuous.</td>
<td>The murals and the projectors were located in a manner that visitors could interact with the projected light.</td>
<td>The projected light covered the entire Murals giving the impression of the complete restoration of them.</td>
</tr>
<tr>
<td>Spirit and Feeling</td>
<td>Although the exhibition tried to replicate the original location, the feeling of the space was not that of the Holyoke Center.</td>
<td>The virtual restoration of the Murals allowed visitors to experience the original colors designed by Rothko.</td>
<td>The projected light conveyed the feeling of the Murals with the virtually restored colors and the preserved matte and gloss surface and brush strokes.</td>
</tr>
</tbody>
</table>

Table 3.2: An evaluation of the cultural heritage dimensions for authenticity and use of projection mapping of the Harvard Murals.

Workflow

The digital restoration of Harvard Murals was a highly collaborative project. It involved experts from various institutions with diverse expertise including conservation, art history, chemistry, technology, and color science. Before they started to work on the Rothko’s murals, they had to prove the concept of changing the color from one to the other first by collaborating with the MIT Media Lab on a small scale mockup. Once it was proven that this concept could be executed, they started the project.52

The initial step was to gather information of the original colors of the murals by restoring photo slides and investigation of the undisplayed sixth mural. The team developed a custom-made software in which they could geometrically and radiometrically calibrate the compensation images using the information they found from earlier studies. The last step after the installation was to calibrate the ambient lighting to achieve the desired effect

of the projected images onto the murals. The process was adjusted along the way and was described as iterative through trial and error.\textsuperscript{53}

![Diagram showing the workflow of the Harvard Murals projection mapping project. Image: Preme Chaiyatham](image)

**Figure 3.2.5: A diagram showing the workflow of the Harvard Murals projection mapping project. Image: Preme Chaiyatham**

### Hardware and Maintenance

There is no information on the model of the projector used in the actual exhibition of this project. However, the projector used to perform the restoration during the research was Optoma TX1080 projectors with 1920 x 1080 resolution (approximately $1300$ depending on supplier). The projectors had a brightness of 3600 lumens and a 2200:1 contrast ratio.\textsuperscript{54}

In the exhibition, the projectors were installed on the ceiling about 12 feet away from the murals. After about four months of display, the bulbs needed to be replaced as they lost their intensity. Although the cost for the hardware was unidentified, according to Narayan Khandekar, the overall cost of the project was about a million dollars.\textsuperscript{55} This was due to the collaboration between experts in the field and also the experimental nature of the project.


**Figure 3.2.6: The placement of the projectors during the exhibition Image: Harvard Art Museums, Terry Winters on Mark Rothko’s Harvard Murals, https://vimeo.com/133748854. Accessed Dec 16 2021.**

\textsuperscript{53} Narayan Khandekar.
Because they were not short throw projectors, they needed to be installed quite far away from the murals. This increased more chances for the viewers to block the projected light. Instead of being an obstruction to the exhibition, this was an opportunity for the viewers to block the light with their hands to see the original deteriorated state of the mural, the compensated mural, and the compensation light on their hands at the same time. (Fig 3.2.7)

![Figure 3.2.7: Visitors blocking the projected light.](Image: Harvard Art Museums, Terry Winters on Mark Rothko's Harvard Murals, https://vimeo.com/133748854. Accessed Dec 16 2021.)

Feedback

The feedback of this digital restoration of the murals could be described by two groups, the public and the experts. From interviews conducted by the Harvard Art Museum, visitors were prone to be excited about the exhibition. Right at 4 pm every day when the projectors were shut off, there would be a spontaneous applause, gasp, and praise. One visitor said that "it's such an amazing experience, ... even knowing what would happen, I was surprised." Another said that "he hadn't expected the color contrasts to be so extreme." 56

The other feedback came from experts in the conservation field. The study day of the Rothko-centered programming for scholars, students, and the public provided insightful perspectives from professionals in the field. Mary Schneider Enriquez, the museums' Houghton Associate Curator of Modern and Contemporary Art, highlighted the issue of the appropriate procedures to take in order to protect, care for, and enable a piece of art to be what it should be, based on the artist's wishes and on historical precedent. As several participants remarked, the application of light to Rothko's paintings effectively generated two versions of the mural series: the color-corrected works that take viewers back to the 1960s; and the unlit "originals" that bore all the deterioration and subdued colors of the past. 57 However, another scholar emphasized the need to distinguish that the paintings were not restored, but their appearance was. Even in their natural condition, these are very vigorous runes. 58 At the events, comparisons of the two versions and judgments of their

respective authenticity and validity arose frequently which proved that the exhibition was successful in generating discussion, fulfilling the museum director's aim to use this as a major opening exhibition.  

There was opposition, however. Terry Winters, a modern American artist, as well as a number of others, confessed that his original choice was for the murals in their unrestored state, despite his appreciation of the digital restored one. “I was kind of shocked, actually, that once the lights went off, I felt as if Rothko had entered the room, ... somehow, the transformation just revealed another aspect of the paintings, and of Rothko's presence. ... I was happy seeing the restored paintings ... but the unrestored Murals give another feeling, which I found very moving: the loss of color, the loss of time.”  

Jeffrey Weiss, a senior curator at New York’s Guggenheim Museum, despite his reservations about the conservation process used on the Harvard Murals, described the project as “world-historical” and “a crossroads” for the discipline. He strongly suggested that the field must be able to comprehend new technology and engage with it critically.  

One artist apparently voiced dissatisfaction with the whole effort, claiming that light reflected off a canvas was fundamentally different from the light allegedly emitted by a Rothko. Although paintings could not produce light, certain pigments, such as alizarin (what Lithol Red imitates), reflect both visible and UV light. While the human short-wavelength photoreceptor has a peak absorption at 426 nanometers, it could extend into the virtually ultraviolet, and individual human variation allows some individuals to sense blue light more powerfully than others. Some individuals may have seen a fluorescent brightness in the original pigments and it wasn't even there in the re-lit restorations.  

Apart from the concern on the visual effect of this project, Ken Okiishi, an artist, voiced that the sound created by the ventilation of the projectors was very distracting. However, an art historian, Yve-Alain Boise, did not perceive the existence of the projectors in space at all.  

Despite the debate, some experts felt that this type of digital augmentation will become more accepted and mainstream in the art world in the near future. Others embraced digital tools to investigate issues of originality and materiality.  

Findings  

This project demonstrates the process of radiometric calibration. To obtain the level of precision required for the compensation images that resulted in the proper colors for the virtually restored murals, a sophisticated approach involving many parties of specialists was required. Additionally, the exhibition's setting allowed viewers to get close to the murals. This prompted people to engage with the murals, blocking light with their hands or papers in order to see both the compensating projected picture and the original. At 4 p.m., the projectors were turned off, allowing visitors to enjoy the unlit originals with their subdued colors of time. For these factors, this project conveyed the authenticity of the artworks.

60 Mitchell, “Up for Debate.”  
61 Ibid.  
62 Adam Rogers, “How These Rothkos Were Restored Without Touching the Canvas,” The Daily Beast, May 30, 2021,  
https://www.thedailybeast.com/how-these-rothkos-were-restored-without-touching-the-canvas?ref=scroll.  
64 Ibid.
Additionally, this experiment indicates that this technique may be used without impairing the artifact's light sensitivity, as the projector's actual light power on the projected surface was only 25 lux. Due to the experimental nature of this project, it took several years to complete. Additionally, the project’s total cost exceeds a million dollars due to the resources spent on research, experiments, and field expertise. Finally, this initiative sparked debate among art professionals about the validity and authenticity of the virtually restored versions, which was critical for feedback and integration of this technology into the field.

3. Sant Climent de Taüll

![Sant Climent de Taüll, Catalonia, Spain](image)

**Figure 3.3.1: Sant Climent de Taüll, Catalonia, Spain**

*Image: Centreromanic*

**Project Overview**

A virtual projection mapping has been projected onto the twelfth-century apse of Sant Climent de Taull since 2013. The digital visualizations are shown in three phases over the course of thirty minutes. Visitors can see the cathedral in three main forms including: as it is today without augmentation; with its restored frescoes, which are now in museums, superimposed over the physical ruins; and as part of an audio-visual projection mapping presentation called #taull1123, transporting back to 1123 when it was built.65

The exhibition emphasizes major periods in the church’s history, beginning in 1123, when its apse was freshly painted with famous religious symbols, and ending in the nineteenth century, when the building was rediscovered. The goal of this mapping is to visually and digitally repair the original paintings to be able to envision and duplicate the entire pictorial set as it was in 1123. The video presentation assists visitors in understanding the painting method of Romanesque frescoes as well as discovering numerous iconographic depictions that have made this creative and religious art work so renowned.66

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Figure 3.3.2: (From left to right) The original apse with faded original pigments, the virtual restored apse with the image of the fresco exhibited in the Museum, and the virtual restoration of what the apse might have looked like in 1123. Image: Burzon Comenge and Playmodes, https://pantocrator.cat/projectes/, Accessed Dec 18, 2021.

Eloi Maduell. Playmodes Project and Technical Production
Santi Vilanova. Playmodes Soundtrack
Albert Burzon, Xavi Mula Illustrators
Albert Burzon, Eloi Maduell Animation
Carlos Padial 3D Modeling
Captae 3D Scanning
Antonio Sáinz. Haz Luz 17 Lighting Design
Josep Giribet. Calidos Photography and Textures
RC Enginyers Electrical Engineers
Management Team: Eva Tarrida i Sugrañes,* Architect
Montserrat Cucurella-Jorba* Architect
Pere Rovira i Pons* Restoration
Jordi Camps i Sòria* Conservation
Merce Marquès. Krom Paint Restoration
Research Team: Eduard Riu-Barrera* Archeologist
Albert Sierra i Reguera* Historian
Isidre Pastor, Maite Rovira Archeological Studies

*Sant Climent de Taull History

Located in Taull, Catalonia region of Spain, the Sant Climent de Taull is a basilica-structured church with three naves and an attached bell tower. Although the exact date of construction is uncertain, the church was consecrated in 1123. The church is a Romanesque church that was heavily inspired by the Lombard style, as seen by its external ornamentation. Unlike other churches of the period, the church was meant as a site of
Christian worship rather than a pilgrimage. The artwork at Sant Climent de Taüll was crucial in bringing art into the public. The mural painting on the church’s central apse is the principal piece of art, the Christ Pantocrator, which has all of the stylistic features of Christological representations, including, expressive solemnity, the oval/circular niche, the crimson that represents the figure of Christ as the beginning and end of all things, and the symbolic representations with animal forms used to show the evangelists. The painter’s name is unclear, however he is referred to as Master Taüll. The church was designated as a world heritage site along with other churches in the region by UNESCO in 2000. The importance of this fresco has been widely recognized today as it was voted in 2014 as the most representative painting of Barcelona.

Starting around the 1910s, important Catalan frescoes were purchased by private owners like the one in Santa Maria de Mur. To save these Romanesque frescoes in the Catalan Pyrenees from being sold abroad, the Junta de Museus in Barcelona started a purchasing campaign from 1919 to 1923. The fresco at Sant Climent de Taull was relocated from the original site, as part of this salvage mission, by the authorities to Barcelona in 1920 and has been exhibited since 1924 at the Museu Nacional d’Art de Catalunya (MNAC). This original fresco would serve as a starting point for the visualization of the projection mapping later.

Since then the church was left with nothing but an empty apse with little remains of the fresco. To solve this issue, Ramon Millet was commissioned to recreate a replica of the fresco in 1959 at its original location. However, in 2012, the replica deteriorated through time showing cracks, fading colors, and moisture damages. Furthermore, the replica plaster was mounted on metal supports which were intended to be temporary. The Catalan authority needed to take action to solve this problem and to attract more visitors as it declined throughout the years.

The project was funded by the Catalan Government’s Ministry of Culture and the "la Caixa" Foundation in 2012 as part of the "Open Romanesque" initiative. The first option considered for the restoration was to create another replica of the fresco. However, a study of the 1920 removal revealed layers of surviving paints that the 1959 replica concealed. Additional research was conducted to ascertain the presence of these pigments behind layers of whitewash and indigo-white. Once established, the project’s primary objective swiftly included the recovery of these original painting remnants.

At the same time, another option for restoration was considered, a projection mapping project to render the apse to its restored original and its recreation of what it might have looked like in the early twelfth century. Because this was consistent with retaining the deep layers of Romanesque paintings, this technique had a significant benefit in that it

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72 Ibid, 14.
73 Albert Sierra, “#Taull1123: Immersive Experience in a World Heritage Site (or Augmented Reality without Devices).”
allowed the church’s authenticity to coexist together with the ability of viewing the restored frescoes in situ. When combined with an audiovisual method, this direction had the potential to convey the significance of the site to visitors in a straightforward and moving manner. Eventually, the projected light was chosen for the restoration with the overall cost of $400,000.74

Design Process

Once a decision was made that the projection mapping was suitable, four criteria for the project were established. Firstly, the church’s aesthetic and architectural characteristics had to be maintained. This necessitated that any projection-mapping equipment would have to be hidden from view of visitors. Secondly, maximum picture quality for detail and color would be required because of the artistic quality and size of the artwork. Thirdly, with the three dimensionality of the space in mind, the projection needed to align precisely with the building’s fabric as well as the remnants of the frescoes. And lastly, this projection mapping could not be perceived as an independent exhibition but rather a complementary factor augmenting the perception of the site. This meant that it was necessary to make it coherent with other restoration taking place there.

These criteria necessitated four areas of conservation for the project which included scientific studies, architectural restoration, artistic restoration, and projection mapping. Rather than proceeding separately, the project integrated every aspect of the work together, namely conservation, lighting design, architectural design, museography, art restoration, and projection mapping. While there were several preservation actions taking place, such as fixing the roof, this thesis focuses only on those that related to the creation of the projection mapping replica.

The first step for the virtual restoration of the apse was to remove the 1959 replica of the fresco. Once dismantled, layers of indigo-white concealing the original medieval paints were discovered. A team of conservators spent four months repairing gaps and cracks and removing this modern overpaint layer to reveal the original remnants of the fresco.

![Figure 3.3.3: A team of conservators removing the 1959 replica revealing the original pigments.](https://vimeo.com/87102885?embedded=true&source=vimeo_logo&owner=24526031)


After the projected surface was prepared, a 3D scanning of the apse was carried out to create a simplified version of the digital meshed model. This model was used to superimpose the photographic documentation of the frescoes in the museum and in situ. The technologist, illustrator, and photographer needed to collaborate together after a 3D...
model was generated to unfold the topography of the apse. The unfolded model was necessary to produce the drawing and animation for the show.76

Figure 3.3.4: 3D Scanning process for the study of the apse's geometry

Once the visualization was ready, it was tested on the rough and ochre-colored apse wall. The result was satisfactory due to the quality of the projectors chosen.76 With current technology, intensity of the light from each projector was varied to achieve a coherent light level and effect harmonizing the virtual replica with the physical fabric of the apse and surrounding areas. There was a concern about the damage that the projected light could have done to the remaining fresco. However, it was proven that the light from projectors had lower intensity than the interior lighting. Thus, it was safe for the final implementation.

The projected area was roughly 1075 sq.ft. in total. To tackle the irregular shape of the apse, large area of projection, and the intention to hide the hardware from visitors’ view, three pairs of projectors were installed, one above the entrance; one on metal supports in the side aisles; and one behind the reconstructed flooring in the apse. (figure 3.3.5) The combination of multiple projectors ensured even focus throughout the depth of the apse and enhanced the resolution six times, rendering the pixels noticeable. Two computers were also hidden above the entrance to control six projectors synchronizingly.

76 The projectors used in the project were from Christie, a manufacturer of high quality projectors for large venues. The models used here included DHD550, DHD675, and G-Christie serie projectors; Rajinder Sodhi, “Saint Climent de Taüll – First Permanent Projection Mapped Church,” Projection Mapping org, accessed December 9, 2021, http://projection-mapping.org/mapping-sant-climent-de-taull/.
The outcome of the replica was a cycle of different projections showing three phases of the fresco including the remnants on-site, the superimposed fresco at MNAC, and the hypothetical replica called #taull1123. A study of the way visitors explored the church was conducted to determine the appropriate time for each cycle. The result was a 30-minute projection mapping show dividing into three minutes for the remnant on-site, seventeen minutes on the MNAC original, and ten minutes on the #taull1123.

Much of the visualization effort went to the last show, #taull1123, since its purpose was to transport the visitors back to see what the apse would have looked like in 1123. With only few remnants left, this digital recreation needed to be hypothetical based on the original frescoes relocated to the MNAC. Keeping this restraint in mind, the show was perceived as a narrative to highlight some significance of the fresco including the process of creation, formal qualities, layers of colors, and the iconography on the work. This was achieved through the individualization of each character of the artwork, paying particular attention to the most important motifs.

The storyline was developed in collaboration with MNAC. The final outcome was focused on the frescoes and its creation using lighting techniques to narrate the detail. The main goal was to transmit knowledge without narration and “not only to revalue the aesthetic aspect of the pantocrator (a title given to Christ as the universe’s ruler, particularly in Byzantine church decoration) but also to regain its meaning and facilitate its readability, all while respecting its historical value.” It was not aimed to be didactic but rather to help visitors see and remember the painting and to transport them back in time, to the moment of its creation.

The final presentation was accompanied by a soundtrack. It was a combination of the sound of the valley and of the church. The overall composition was contemporary, however, one could still feel the medieval tone from instrument and timbre adding an enhanced experience for the visitors.

The digital recreation posed several difficulties during the process. Firstly, physical deterioration on-site like cracks, marks from earlier removal, and missing pigments made it harder to work with. Combined with different dimensions of the photographic documentation of the relocated fresco at MNAC, the team needed to make sure that the digital replica aligned well with them. Secondly, the restored apse surface was not a clear canvas, the remaining pigment in situ needed to be incorporated into the new digital reconstruction. The team had recovered and redrawn them from remaining details to study and compare with other fragments. Lastly, there were sections of the apse that the frescoes were totally lost, so a complete digital recreation needed to be done. However, through the studies of geometry, colors, and decorative elements, together with the Romanesque style of patterns, rhythms, and measurements, it was possible to follow existing remnants and create the missing parts.

78 Albert Sierra, “#Taull1123: Immersive Experience in a World Heritage Site (or Augmented Reality without Devices).”
Evaluation

Visualization

One of the most difficult aspects of this project was the three-dimensionality of the apse. With the semi-dome structure and the depth of the apse, multiple projectors needed to be used to cover the depth of field and increase the resolution of the projection. The surface of the apse was repaired as part of the restoration after removing the 1959 replica to show the original Romanesque fresco. Thus, the wall was relatively smooth for the projection. The remnants of the pigments on the wall created another difficulty, however. The team needed to align the projection with these pigments in relation to the photographic documentation of the removed apse at MNAC which was adjusted to a different dimension. Furthermore, the projection needed to be of highest-resolution possible while maintaining the historical atmosphere of the site. This was done through the calibration of the light intensity of the projector to make sure that the projection blended well with other areas and not be perceived as an independent exhibition. Lower brightness also ensured that no photo-damage would be done to the historical surface of the apse which was one of the most important criteria of the project.

Presentation

The presentation was divided into three parts in the thirty-minute show. Before the show started, visitors could move freely in the church to explore other exhibitions. The light was dimmed down once the show started and the projection became the only illuminated part of the church, drawing attention from the visitors. The custom-made soundtrack using Medieval instruments accompanied the show to immerse the visitors with the experience. Throughout the show, several techniques were employed. Outlining and painting the colors were mainly used along with lighting techniques such as spotlight and glowing effect. One of the lighting effects that was suitable for the site was the candle light illumination. The flickering effect helped transport viewers back to the atmosphere of medieval times. Toward the end of the show, white flood lights illuminated the whole apse showing just what remained there. This reflective moment was quite powerful since it was a stark contrast to the colorful past of earlier presentations, making visitors aware of the deterioration of the original fresco.

Figure 3.3.6: Multiple scenes from the light show.

Content

The content was developed together with the MNAC. Without narration, the show did not transmit much knowledge of the frescoes and the site to visitors since it was their aim not to be didactic but rather to make people remember the frescoes and expand their experience of the site. To achieve this, they used lighting techniques to highlight the significant parts of the frescoes by showing the process of creation, formal qualities, layers of outline and colors, and the iconography. The visual was also augmented by an accompanied soundtrack which gave a medieval feeling to the whole experience.

The study of visitors’ behavior on the site informed the structure of the content. From this study, it was agreed that the show should be thirty minutes long, with three minutes for the remnant on-site, seventeen minutes focusing on the MNAC original, and ten minutes for the #taull1123 complete reconstruction. For this time frame, the visitors could experience the projection mapping in a 30-minute interval from 10am to 2pm and 4pm to 7pm. This time table, while it might obstruct visitor experience as they had to see the show from the beginning to immerse in the full experience, was useful in that viewers could plan visits accordingly.

Figure 3.3.7: A comparison between the restoration by projection mapping (left) to the original blank apse (right)


Accuracy and Authenticity

The accuracy of the digital reconstruction of the frescoes derived from the relocated original at MNAC. Thanks to the high-definition photographic documentation of it, the team was able to project it seamlessly onto the apse with little adjustment. And because the project had access to the 3D scanning technology, the geometry of the reconstruction could be precise to millimeter scale. With access to the site, combined with high-quality projectors utilized, the colors were accurately calibrated on the soft ochre-color of the apse.

In terms of accuracy of content, it could be divided into two categories; the damaged parts and the missing parts. For the first one, the paintings were deteriorated but still had some details left. The reconstruction completed the characters from these details. The second part, which had no pigments left on the wall, was developed following the characteristics of the other parts of the frescoes exhibited in the Museum. Although this process was done with extensive research, it was partly based on speculation. Thus, its accuracy and authenticity were compromised.

Figure 3.3.8A shows the reconstruction of the part where little details were left. In this case, it was the position of the apostle’s hands that gave hint to the gesture and position of the character. Figure 3.3.8B utilized the existing details from other elements to recreate the
completely missing part. The illustrator, Albert Burzon, and project manager, Eduard Riu-Barrera, had studied multiple aspects of the remaining fresco to precisely recreate the missing part, including shapes, colors, volumes, brushstrokes, and postures. They had not “invented anything, they are simply copies of existing things.”

Figure 3.3.8A and 3.3.8B: The process of digital reconstruction based on the existing elements

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80 Resum de La Restauració a Sant Climent de Taüll, accessed December 21, 2021, https://www.youtube.com/watch?v=-CS_KF4qUbA&list=PLR_E_85NaaaFxRk7IS2dYu4vVHurbpINW&index=12.
The projectors were hidden from visitors' view. Although some alterations of the site were necessary, its design did not disrupt the historical setting of the site.

The exhibition was a reel of 30-minute light show, allowing visitors to interact with the apse with and without projection mapping. The projected content was seamlessly aligned with the geometry of the apse due to the sophisticated processes by the visual technologists.

The final exhibition was designed to allow the visitors to view the apse original materials without projected light. Visitors could view the apse with the original faded pigments from the thirteenth century, the virtually relocated fresco in MNAC, and also the projected 1123 appearance. The first two shows were accurate in terms of both design and colors due to the close collaboration of the conservators and visual technologists. However, the last show was speculative based on extensive research.

The installation of all hardware was designed to minimally disrupt the historical setting of the church and allow the church to continue its liturgical uses. The projection mapping expanded the use of the church as a museum for visitors, besides being used as a religious place.

The installation of the hardware was custom-made to ensure that it was reversible and not disruptive to the atmosphere of the church. The content demonstrated the techniques of painting used by medieval painters, including color backgrounds, black profiles, shadows and light, and brushstrokes. The ultimate result resembled a light show which can be seen as inauthentic.

The location of each projectors was appropriate for the site as they were hidden from visitors' view. The show was played repeatedly throughout the day, so the visitors could watch it without any interaction. The first two parts of the show depicted the original empty apse and relocated fresco, which accurately represented the site. Although the last show demonstrated what the apse might have looked like in 1123, it was based on speculation and featured animation which may be seen as not appropriate for the site.

The design of the show gave an immersive experience of the place, evoking a sense of historical feeling of the church. Because of the accurate projected content in the first two versions, visitors could feel the spirit of the place temporarily.

**Table 3.3: An evaluation of the cultural heritage dimensions for authenticity and use of projection mapping of Sant Climent de Taull.**

**Workflow**

The making of the project was a highly collaborative process. Because of the complexity of the project, four areas of work were integrated together which were scientific studies, architectural restoration, artistic restoration, and projection mapping. The project included architects, conservators, restorators, historian, archeologists, lighting designer, photographer, and the audiovisual team.
The first step was to remove the replica apse and restore the original wall to prepare the surface for the mapping. 3D scanning was done after the physical restoration to generate a 3D model necessary for the drawing and animation. Photographic documentation was done at the relocated original apse at MNAC for the mapping and illustration. After all the materials were ready, the projection mapping team, illustrator, sound designer, and lighting designer worked together to create the mapping show, in collaboration with the MNAC.

Figure 3.3.9: A diagram showing the workflow of the Sant Climent de Taull projection mapping project. Image: Preme Chaiyatham

**Hardware and Maintenance**

The quality of the projectors was one of the most important aspects for this project. Thus, there were several suitable projectors identified by a market analysis. The criterias were image quality, color, and price. DHD550, DHD675, and G-Christie series projectors from Christie were chosen. To cover about 1075 sq.ft., six projectors were used. The first pair was situated above the entrance along with computers controlling the show. The second pair was supported on a metal platform in the side aisles. The last pair was concealed behind the reconstructed wooden platform inside the apse at a ground level. The distance of the projectors from the wall ranged from 10 to 50 feet. Maximum height of the projectors was 15 feet. All metal platforms were custom made. Vioso AV software and Genfen warping software were utilized for synchronization and playback.

**Feedback**

The project was successful in that it presented three versions of the apse in its lifetime. The exhibition has been well received by the public since the number of visitors had increased by almost 68 percent from 2013 to 2016. Moreover, the project received the

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82 Ramos.
Findings

The use of projection mapping at Sant Climent de Taull has made possible the coexistence of the three versions of the apse. The first one was the original medieval pigments left in the apse. The second one was the projected image of the relocated apse at the MNAC in the 1920s. And the last one was the interpreted 1123 apse. Studies on visitors were done to find appropriate timing for each version. The first two versions of the frescoes were authentic in the sense that they were based on objective documentations of the existing originals. The last show was speculative, despite being based on extensive research. Thus, the authenticity of the last part was compromised. However, this interpretation allowed the visitors to see the evolutions and alterations of the apse through multiple periods while leaving the apse untouched to continue its deterioration and its function as a living document of the site.

The incorporation of the hardware on-site was almost seamless because they were hidden from visitors’ sight which allowed the historical atmosphere of the site to appear almost undisturbed, augmenting the authenticity of the site. This was made possible through some modifications of the site including customized metal platforms and wooden altar. As a result, this project showed that sometimes it was necessary to introduce new elements to the site in order to minimize the disruption of the historical atmosphere.

Highly sophisticated technology like 3D scanning was also necessary for the complex geometry of the apse. There was sophisticated technology and software used, including Christie projectors (a major brand of projectors used in large projects and venues) and 3D scanners. As a result of these factors, the project’s cost was approximately $400,000, which was made feasible by the Catalan government and a foundation. Despite the very sophisticated methodology, the project was completed in just over a year. To optimize the immersive experience of the projection mapping, other techniques needed to be developed in tandem with the mapping including lighting and sound design. The project’s procedure necessitated the collaboration of various professionals. The four criteria of the project, established in the beginning stage of the project, ensured the authenticity of the project.

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4. Thomas Cole House Museum

![Figure 3.4.1: East Parlor, Thomas Cole House, Catskill, New York. Image: Premchai Chaiyatham](image)

Project Overview

In 2017, an immersive exhibition telling the story of Thomas Cole was opened to the public at the Thomas Cole National Historic Site in its east and west parlors on the ground floor. The project took more than ten years to complete bringing expertise in the fields of art history, historic interiors, education and theatrical production. Second Story Inc., a globally recognized design studio, created the multimedia exhibit, which included music and moving images, making visitors step into Thomas Cole’s story inside the Parlors. The experience features paintings that “come to life” with Cole’s own words, which are given voice by noted actor Jamie Bell. In the east parlor, Cole’s letters to his contemporaries “magically emerge” on desk surfaces to tell their narrative. All of these captivating exhibitions are done with projection mapping technology which lift the bar for small house museums. The project has been made possible by a major grant from the National Endowment for the Humanities: Exploring the human endeavor, the Institute of Museum and Library Services MA-10-15-0116-15, Empire State Development’s Market NY program, Hudson River Valley Greenway, Herzog’s of Kingston, Eli Wilner & Company, and Geoff Howell Studio. The total

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grant of approximately $600,000 was split in half between the restoration and the projection mapping installation.\footnote{Elizabeth Jacks, Thomas Cole House, interview by Teerat Chaiyatham, Zoom meeting, November 18, 2021.}

The Parlor is effective in conveying Cole's innovative creativity as well as the reality of his life as a professional artist with patrons to please. The project was so successful, drawing visitors of all ages, that another projection mapping exhibition was recently opened on the second floor in late 2021.

![East Parlor Exhibition, Thomas Cole House, Catskill, New York.](https://segd.org/parlors)

Management Team: Heather Paroubek, Project Manager
Elizabeth Jacks, Director
Lisa Fox Martin, Chairman

Research Team: Jean Dunbar, Carrie Feder, Historic Interior Consultant
Kate Menconeri, Chief Curator
Warner Shook, Theatrical production
Nancy Siegel, Art History
Alan Wallach, Thomas Cole Scholar

Projection Mapping Team: Second Story, Potion Design


**Thomas Cole House History**

John Alexander Thomson and his brother Thomas Theodore Thomson erected a house in Catskill, New York, in 1814–1816 to house their extended family, which included Thomas Cole, the now-famous Hudson River School painter. The well-known landscape painter Thomas Cole was strongly associated with Cedar Grove, which is why the location is now recognized as the Thomas Cole National Historic Site. Cole was born on February 2, 1801 in Lancashire, England. He immigrated to the United States with his family in 1818 and lived in a variety of places, including Steubenville, Ohio, and Philadelphia, Pennsylvania, before arriving in New York City in 1825, at the age of 24. He started spending summers in Catskill while residing in New York. Following his short first visit in 1825, he became a
frequent guest in the town, visiting for lengthy amounts of time in many of the summers that followed making him acquainted with Thomsons.

After their marriage in 1836, Maria and Thomas Cole shared Cedar Grove with John Alexander Thomson, Maria's sisters, slaves, and, eventually, their children. The Coles had a suite of three rooms on the second floor. Until his first studio was completed in 1839, he painted in the home, most likely in a tiny, unheated chamber off the sitting room.

Cole lived there until his death in 1848, producing a number of landscape paintings. He was a founding father of the Hudson River School which flourished in the mid-19th century. The site and nearby landscapes retain a high degree of integrity as the relatively unspoiled home, workplace, and source of inspiration for the father of American landscape painting, Thomas Cole.88

Design Process

The project started with the restoration of the interior of the house in 2008 when the site received a planning grant from the government. The museum team traveled around the country to look for inspiration and to study what had been done in museums and historic houses.89 They understood from the start that they wanted to include technology into the telling of the site’s story, but they kept an open mind. The team was drawn into the use of technology with subtlety, integrating it into the historic decor. Eventually, they decided to utilize projection mapping as a main tool, combining it with the recent interior restoration to tell the story of the site.

Before this project took place, Thomas Cole’s house was just like any other house museum because of an absence of Cole’s stories.90 Thanks to printing technology, some replicas of his paintings were installed in the house, however, the museum wanted people to meet Cole without the paintings because visitors were there not only to see objects but to meet the historical people. Because of this motivation, six internal experts at Cole’s house, representing diverse skills in historic preservation, theatrical art, storytelling, along with a curator and a director of education, worked with scholars on Thomas Cole, for example, people from the Metropolitan Museum of Art, to piece together the stories and interpretations that they would like to transmit to the public.

According to Elizabeth Jacks, Executive Director of Thomas Cole House Museum, the research process took a long time (almost ten years) to complete for many reasons. Most of the literature about Thomas Cole mainly focused on his artwork and not his life or his house. The research for this interactive exhibition was also carried out in parallel with the restoration of the house which prolonged the process since there were no existing photos of the interior. The process required a tremendous amount of discussion and adjustment, resulting in an interpretive plan which focused on the nineteenth century.

With this established plan, the team went back and forth on the draft and finally passed it along to Second Story, an experiential design company with expertise in the art of storytelling across cultural and brand environments. The storyline in the initial draft was too long, according to the firm. They had recommended some changes and stories to incorporate into the main narrative of the exhibition. This collaborative work between the museum staff, outsourced professionals, and experts in Thomas Cole ensured that the end

90 Elizabeth Jacks, Thomas Cole House.
product would not misinterpret the narratives since it was the main goal of the museum not to change the words of Cole.

Once the narrative had been established, the location and method of presenting the stories were discussed. The east parlor was chosen to tell the main story of Thomas Cole because of its uninterrupted wall offering more surfaces for the projection. The west parlor, while it had less wall surface, was more of a formal room where the patrons might sit and have "conversations" with Cole. Thus the narrative in this room told of the interaction between Cole and his patrons describing how his paintings were made.

![Figure 3.4.3: East Parlor, Thomas Cole House, Catskill, New York. Image: Preme Chaiyatham](image)

The design firm needed to travel to the site three times over the course of two years to create a site-specific installation. In the west parlor particularly, many possibilities were discussed for the placement of the projectors, for example, hiding them with the lighting fixtures from the ceiling and projecting onto the central table. In the end, the projectors were hidden behind the picture frames and a cabinet projecting contents in letters onto side tables. The first exhibition, opened in 2017, was so successful that the museum initiated another multimedia exhibition on the second floor using a television screen and projection mapping.
**Evaluation**

**Visualization**

The exhibition has three components, the east parlor, the west parlor, and Thomas Cole’s studio on the second floor. Inside the east parlor, high-resolution images of his paintings are projected onto seven white surfaces which are picture frames and curtain blinds. In the west parlor, on the other hand, his hand writings along with some of his works are projected onto blank papers on tables to narrate his correspondence with his patrons. The last exhibition utilizes a combination of projection mapping onto three blank walls and a television screen. The screen is covered with a canvas making it look like a blank painting frame while allowing the content to shine through.

![Figure 3.4.4: (From left to right) Projection mapping exhibition in the East Parlor, the West Parlor, and the second floor Image: Preme Chaiyatham](image)

**Presentation**

The exhibition is part of a guided tour by a museum staff in the course of about an hour. The first exhibition in the east parlor requires all visitors in the group to sit down first before the staff starts the show. All windows and doors need to be closed during the course of five minutes to block sunlight and noise which may disturb the exhibition. While this way of presenting makes sure that the visitors get the full experience, other tour groups need to wait outside the parlor for the next round which may cause an interrupted experience with the visit.

On the other hand, visitors can explore the west parlor freely. There are three projection mapping systems hidden behind painting frames and a cabinet controlled by motion sensors. The content will appear on the papers on the table as visitors approach them. This method makes it easy for visitors to explore each table and watch the content. However, it is difficult to do so while listening to the staff at the same time. The space is filled with natural light from large windows, making it difficult to see the content on the paper clearly.

The last exhibition is in a small room that was Cole’s studio. Because of the limited space, the room can afford only about four to five visitors each time. Thus, the tour group needs to be divided to take turns watching the show in the enclosed room. While waiting for the exhibition, the other half of the group can learn more about the site by a narrated story from a speaker on the ceiling while exploring objects inside the room.

Because of some restraints posted by the guided tour, the museum also offers an unguided tour during the weekends. This is a good opportunity for visitors to explore the house freely and encounter the projection mapping exhibition without interrupted experience. Museum staff are stationed in each room to give more information to the visitors.
Content

The content for each projection mapping exhibition inside the Cole house focuses on his artwork and him. The east parlor mainly uses his paintings which come to life once the exhibition starts to tell the story. Thomas Cole manipulated the scale of his landscapes to make you feel smaller. In response, the design team opted to go large and engulf visitors, allowing them to experience Cole's art in a manner that no one else could, infusing them with wonder. The array of canvases comes to life, flooded in the rich hues of Cole's paintings, while guests listen to famed actor Jamie Bell's audio narration as he shares Cole's deepest thoughts on his beloved Catskills, his treasured family, and the growing cost of development. It is like having a conversation with Cole himself. The story closes with a thought-provoking question for guests to ponder as they leave the chamber.91

The west parlor offers untold stories about his relationship with patrons like Ithiel Towns. It shows his views on the paintings which are not aligned with the commissioners through sets of letters. Portraits, animated handwriting, drawings, and sketches make up the visual display. Each one concludes with a challenging question for visitors to consider and debate.

Accuracy and Authenticity

Because Cole's paintings played significant roles for the exhibition and there were none of his actual paintings in the house, a high-definition photographic documentation needed to be executed. The museum team focused on this process to get as accurate as possible for both the details and colors. The photos taken were color-calibrated by comparing with published replicas. The rectified colors were, then, sent to the company, Second Story, to incorporate in the visualization of the show. On site, it took about a week for the set up of the hardware to make sure that the projected contents were aligned perfectly with the surfaces.

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<th>Form and Design</th>
<th>Design</th>
<th>Interaction</th>
<th>Content</th>
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<tr>
<td></td>
<td>The design of the project took advantage of elements inside the house. For example, picture frames and blank canvases, which were objects related to the owner, were used to be surfaces for the projection. Moreover, they were installed and hidden in ways that enhanced the experience of the visitors.</td>
<td>The exhibitions encourage interaction from visitors. For example, motion sensors were used to trigger the projectors in the West Parlor. The East Parlor and second floor exhibition allow visitors to immerse themselves with the owner of the site.</td>
<td>The projected contents are applied to new elements created for the exhibition and do not enhance the understanding of the design of the site, but give knowledge about the artist, his works, and the surrounding landscape. Extensive research was conducted to ensure the accuracy of the interpretation.</td>
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<th>Materials and Substance</th>
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<tr>
<td>The exhibitions are not designed to enhance the original materials of the site.</td>
<td>The projection mapping tells narratives about the artist's life and not about the house itself. However, as part of the exhibition, the contents of the house are imparted by the guide.</td>
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<th>Use and Function</th>
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<th>The exhibitions encourage interaction by the visitors with</th>
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<td>The exhibitions enrich the experience of the site as a</td>
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| Tradition, Techniques, and Workmanship | n/a | n/a | The projected contents accurately represent the work of Thomas Cole because of the high-definition photographic documentation done for the exhibitions. |
| Location and Setting | The hardware was installed in a conspicuous way in the East Parlor and on the second floor. In contrast, the installation in the West Parlor is successful in that the hardware is completely hidden from visitors' view. | The West Parlor exhibition encourages interaction by the visitors with the space, while other parts of the exhibition are controlled only by the guide. | The projected contents make visitors understand the landscape and the artist. The knowledge about the house itself is supplemented by the guide. |
| Spirit and Feeling | The design immerses visitors to the artist's house filled with art pieces and objects related to the owner. | The interaction with the exhibitions makes visitors feel like they are talking to the owner due to the voice narration and projected content such as the artist's sketches and handwriting. | The projected contents evoke the feeling of the artist's house. |

Table 3.4: An evaluation of the cultural heritage dimensions for authenticity and use of projection mapping of Thomas Cole House Museum.

**Workflow**

The project was a highly collaborative effort to construct storylines for the exhibition. Since there was not much narrative about Cole himself, much of the effort was put into the research. Experts from multiple backgrounds, both internal and outsourced, put together the drafts in collaboration with the visualization team.

The end products are the combination of the contents and the availability of the space. The stories were established first, then the method of displaying them came later in accordance with the space.

![Workflow Diagram](Image: Preme Chaiyatham)

**Figure 3.4.5: A diagram showing the workflow of the Thomas Cole House Museum projection mapping project.**

Image: Preme Chaiyatham
Hardware and Maintenance

The East Parlor is equipped with five projectors on the ceiling, projecting onto three sides of the walls. The screen surfaces are matte white canvas in forms of picture frames and roller blinds. Because the model used is an ultra short throw projector, the distance of the projectors from the wall is less than two feet. The museum team chose the ‘tried and true’ model for the hardware. They selected the model that had been used for a long time in other institutional settings such as school to make sure that the technology would work well since they did not want to continually update and keep up with the maintenance since there was no technical personnel on-site. However, at some point in the future, the hardware will have to be updated and replaced eventually. The whole system for this room is controlled by a home automation system by Creston. The controlling touch panel is attached next to a lighting switch on the wall at the entrance to the room, so that the staff can easily control the system and lighting. The downside of this system is the visual and acoustical effect of the projectors. The hardware is installed conspicuously on the ceiling and the noise from its ventilators is quite audible. The control panel is also obvious on the wall. A wireless controller, like the one on the upper floor, can be used to minimize this effect.

Figure 3.4.6: Projectors were installed on the ceiling in the East Parlor and the control panel was installed on the wall next to a lighting switch
Image: Preme Chaiyatham

In the West Parlor, three projectors are completely hidden. Because of its smaller size, two mini projectors are installed behind the picture frames. To house the system, the pictures need to be hung on a protruding support structure. Although the projectors are hidden perfectly, the wiring is still visible on the wall. The last projector is placed inside a cabinet so the wiring system can be concealed. To prevent a glare, the glazed panel of the cabinet door needed to be removed. Motion sensors controlling the system are placed on the floor, next to the table's leg. With concealed hardware, this technology is not as intrusive to the historical atmosphere of the house like those in the East Parlor.

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92 Elizabeth Jacks, Thomas Cole House.
The second-floor studio is equipped with three projectors in the ceiling and a standalone monitor in the center of the room. The monitor is covered with a cloth making it look like a painting canvas. Although the monitor requires wiring, the surrounding decorative objects make it look inconspicuous. For this room, the system is controlled wirelessly through an iPad which is located on a cabinet at the entrance of the room. The iPad is installed with an application called Kasa Smart, a home automation system, to turn on and off the equipment. The video and audio are controlled by a custom-designed private website. Because the iPad is handled by the staff upon the arrival of visitors into the room, it is unnoticed and does not interrupt the historical atmosphere of the room. While the projectors are quite conspicuous in this room, the enclosed space does not contain any historic elements, so they did not disrupt the overall atmosphere of the space.

All the hardware inside the museum was installed after the interior restoration. For this reason, they had to remove the floorboards on the upper floor to install the wiring for the system. The process was relatively simple but needed to be done with great care. Each projector is turned on during opening hours which is about seven and a half hours every day.
Because the models used are laser technology, the bulb can work up to 15,000 hours, assuring minimal maintenance.

Feedback

The feedback from the visitors was very positive according to the director of the museum, Elizabeth Jacks. The previous traditional interpretation of the space had extensive text which was too much for the visitors to absorb. The projection mapping exhibition helped them learn a lot of stories about the site. They “sat down and wanted more.”

The exhibitions have been so well-received by visitors that the museum is now planning to incorporate another projection mapping installation in the basement. That project is now in the research process.

Findings

This project demonstrates how projection mapping can be incorporated into a small house museum in terms of hardware, operation, and content. The hardware can be mounted in a highly visible manner, such as on the ceiling, or in an inconspicuous one, such as hidden within a cabinet. This also extends to its controllers, which can range from a wall-mounted panel to a motion sensor to an iPad controlled by a guide. Additionally, this hardware was installed in such a way that it had a little impact on the building’s fabric. Its operation demonstrates that it is managed by museum staff, who are responsible for turning them on during opening hours and activating them when visitors enter the area. Additionally, its content transcends the house’s physical structure. It projects narratives about the owner and his works, pushing the boundaries of what type of content may be incorporated via this technique.

Additionally, this project demonstrates that adopting projection mapping as an interpretative tool for a small house museum requires a significant amount of time, as the project took nearly 10 years to complete. This is largely attributable to the initial assessment of potential technologies, the subsequent research on relevant materials, the production of content, and the implementation. Although this research does not cover the entire financial element of the project, the exhibition was made possible via the use of funds and grants worth approximately $300,000 from a variety of sources. This sum represents a preliminary estimate of the budget required for this type of interpretation in a small house museum employing outsourced professionals.

Conclusion

To conclude, these four precedent applications demonstrate how projection mapping can be incorporated into the preservation field. The Temple of Dendur took full advantage of the non-permanent quality of the technique by depicting multiple possibilities of the original color scheme. The project also exhibited the ability to use this technique in a well-lit space. The Harvard Murals project used the non-invasive technique of the projected light when the traditional methods of conservation were not viable. It demonstrated how this technique could be used to correct deteriorated colors. Moreover, the presentation allowed visitors to interact with the projected light, making them see the two versions of the murals. More importantly, the project pioneered the evaluation of this method, which started a discussion among art professionals. The Sant Climent de Taull project gave an example of

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93 Elizabeth Jacks.
an application within a historic setting. In order to make the presence of the hardware unobtrusive in the space, some modifications were necessary, such as a custom-made altar and metal platforms. It proved that this technology benefits the site by attracting more visitors to the church. The last project showed how this technique could be used to tell narratives about the owner of the site. It also demonstrated various ways to install the hardware and the time and cost necessary for this type of interpretation for a house museum.

Despite the relatively low cost of projection mapping technology in recent years, when combined with the cost of outsourced specialists such as graphic designers and audio-visual technologists, the overall cost of the project can be rather substantial. As demonstrated by these cases, the Temple of Dendur was able to keep costs down by partnership with the Metropolitan Museum of Art's Media Lab, which engaged interns and a fellow to produce visualizations and methods for projection mapping. The Sant Climent de Taull and Thomas Cole House Museum required the services of an outsourced agency. Additionally, the entire cost of the Harvard Murals project exceeded a million dollars due to its experimental nature. Projection mapping projects can cost a wide range based on this information. Moreover, these projects show that expertise from professionals in the fields of cultural heritage and technology is required. Experienced technologists need to develop the projects with insight from conservators, preservationists, and other experts to achieve an authentic interpretation of the site.

Finally, these four applications' workflow can be summarized into five steps. The first phase is the pre-project phase, during which the feasibility of projection mapping used on the cultural heritage at hand is investigated. This approach can include everything from hardware testing to case study site visits. Following verification of the technique's viability, the second stage is research. This includes the investigation of the most relevant materials for both the technique and the interpretation of the site, which requires collaboration with a varied range of parties. The third phase is content visualization. This step is iterative in nature and is dependent on close communication and collaboration between technologists and heritage specialists. The following step is installation and calibration, which can be performed remotely or on-site. However, this phase must be completed in situ for the final correction. These four stages culminate in the project's final result. Only one of the four examples examined in this chapter took a step further to evaluate this technique: the Harvard Murals project. Without this review, it is more difficult to get comments and further develop this strategy for utilizing cultural heritage. The absence of this method will be discussed in the following chapter, which will include an interview with preservation professionals. The findings and the mutual workflow of each application act as a foundation for the guidelines in the following chapter.

Figure 3.5: (Following page) A diagram showing the workflow of projection mapping project for cultural heritage

Image: Preme Chaiyatham
Chapter 4
Experiments

There are multiple gaps of knowledge in projection mapping technology that need to be addressed in order to understand the technology more. The effects of projected light on colored surfaces as well as darker surfaces were largely not researched in existing literature. To explore these questions, two experiments were conducted for this thesis that dealt with the colored surfaces to see how pigments acted with colored light. Moreover, colors with different values and chroma were tested to evaluate the capacities and limitations of the technique. The findings from these two experiments were incorporated into the guidelines in the next chapter.

Furthermore, since projection mapping has rarely been incorporated into house museums for the interpretation of architectural finishes, an experiment was conducted in the Vail House at Historic Speedwell, Morristown, New Jersey for this purpose to comprehend and establish the guidelines for other small institutions. The goal was to incorporate this technique into their site’s interpretation.

4.1 Off-site Experiments

Two off-site experiments were designed to comprehend the effects of light on multiple scenarios which one might encounter on site should this technique be used. They were conducted in the Preservation Technology Lab at Columbia University. The first experiment dealt with different types of pigment and binder while the second tried to see the capacities and limitations in terms of value and chroma of the colors. The results of these experiments helped establish the guidelines in the next chapter.

How light and color interact with each other can give us a better understanding of projection mapping, particularly on colored surfaces, i.e. painted plaster. The light from projectors uses the principle of additive color mixing where primary colors of light; red, green, blue, are mixed together to create virtually any color that we can see. However, the light reflecting from a surface and perceived by the eyes is dictated by the rule of subtractive color mixing. Color is seen on any surface by reflected light that has been influenced by pigments on that surface. Each pigment has a distinct spectral reflectance quality, absorbing some wavelength ranges while reflecting others. The color we perceive is a result of the reflected range. Additional wavelength ranges will be absorbed by mixing more pigments to create new color.

The color human eyes perceive is a relative and subjective quality. Surface color can be quantified by many different systems. One way to identify them mathematically is the use of the spectral reflectance curve which is a curve signifying reflected red, green, and blue wavelengths. Since the perceived color is the reflection of light, what human eyes see is the combination of the spectral reflectance curve of the surface colors and the spectral power distribution (SPD) of the incident light. SPD is different in respect to light sources.\(^1\) Fluorescent lamps have different SPD than light from incandescent lamps, for example. This

principle can be applied to projection mapping on colored surfaces. The SPD of colored light from a projector is combined with the spectral reflectance curve of the surface resulting in the color we see. Although research on radiometric calibration for projection mapping varied with mathematical variables, for example RGB systems, the principle of the spectral reflectance curve could still explain the perceived color.

A. Experiment 1

While each color has its distinct spectral reflectance curve, some different curves may be perceived similarly by human eyes under common lighting. Under natural light or even artificial lights like incandescent or fluorescent light, the colors may look the same to us due to our visual perception called color constancy, a capacity to see colors as largely consistent under shifting lighting conditions. This phenomenon is called metamerism. However, projection mapping may use lights that can be drastically different from our daily life, such as red, blue, or green.

![Figure 4.1: Effects of metamerism under different lighting conditions](https://www.eclat-digital.com/2013/02/22/metamerism/)

Metamerism is a color matching phenomena that happens when two colors appear to match in one lighting situation but not in another. Metameric matching is fairly prevalent, particularly in near-neutral colors such as grays, whites, and dark hues. The range of probable metameric matching decreases as colors get lighter or more saturated. Metamerism occurs frequently when a color is mixed from disparate elements.²

Below is a set of reflectance curves for two colors. A metameric pair is defined when the spectral reflectance curves of two colors intersect at least three times. When two items are metameric pairs, metamerism is evident, and while they may appear to be the same color in some lighting situations, they will not match in other lighting conditions.³

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³ Ibid.
There are two aspects of metamerism behavior of color that affect the projection mapping projects on historic sites. Firstly, it would mean that projection mapping technologists cannot have a fixed formula for radiometric calibration. This is due to the fact that pigments used for architectural paints varied and developed over time. Even though the colors may appear to be similar, they might be mixed from a different set of pigments. For example, the same blues, mixed from different pigments, may perform differently under the same projecting light. This means that every color needs to be calibrated individually.

Secondly, this site-specific color calibration process needs to be performed on-site only. An option to calibrate off-site on a mock up is eliminated. These factors would dictate the time and cost of the workflow of the project.

However, there is a solution for these two effects of metamerism. The metamerism effect can be examined by the use of a spectrophotometer to compare the spectral reflectance curve of the two colors. Moreover, there is software that can visualize the final appearance of colors under different lighting conditions, which makes the color calibration process easier. With this being said, these processes require time and money which can be beyond the means of some projects.

This phenomenon and above mentioned consequences on projection mapping projects form the question for this experiment. To what extent does metamerism impact two similar colors? How much difference would there be with the same colors under shifting lights?

**Methodology**

To prove the extent of this effect, seven pairs of similar colors from different binders and pigments were mixed and applied onto a 100% cotton canvas panel. Each pair represented sample set no. 1 to no. 7. This experiment aimed to measure the visual color difference between the two colors in each color set under natural light and under shifting lighting conditions.

Sample set no. 1 was mixed from the same pigment but with a different binders (acrylic versus linseed oil), while nos. 2 to 6 were made from different pigments in linseed oil binder. Pigments used were artists’ premixed paints available in art supply stores. Information of pigments used in each sample is listed below and represented in figure 4.3.

- Sample 1A - Naple yellow in acrylic binder
- Sample 1B - Naple Yellow in linseed oil
- Sample 2A - Burnt Umber, Titanium white
- Sample 2B - Naple yellow, Titanium white, Vermilion, Scarlet

![Figure 4.2: Reflectance curves of a metameric pair](Image: Bruce Wright, Xrite)
Sample 3A - Ultramarine, Titanium white
Sample 3B - Phthalo Cyan blue, Cerulean blue, Naple yellow, Titanium white
Sample 4A - Ultramarine, Cadmium red, Titanium white
Sample 4B - Phthalo Cyan blue, Cerulean blue, Vermilion, Scarlet, Naple yellow, Titanium white
Sample 5A - Naple yellow, Ultramarine
Sample 5B - Viridian green, Cerulean blue, Naple yellow, Scarlet
Sample 6A - Cadmium red, Titanium white
Sample 6B - Vermilion, Titanium white
Sample 7A - Naple yellow
Sample 7B - Naple yellow, Cadmium red, Titanium white, Yellow ochre, Cerulean blue, Burnt sienna

Figure 4.3: Seven pairs of similar color samples mixed from different pigments under natural light
Image: Preme Chaiyatham

This experiment used the CIELAB color space to quantify the visual color differences between the two colors in each color set. CIELAB color space represents color as three values: L* for perceptual lightness, a* for redness or greenness, and b* for blueness-yellowness. These numbers were used to calculate the delta E value, a standardized unit of measurement defined by the Commission Internationale de l’Eclairage that measures the difference between two colors. The delta E value was calculated using the Delta E 76 formula (Figure 4.4), which was developed in 1976 by the International Commission on Illumination (CIE).
The delta E value of each sample set under natural light was measured to define the color difference of the two colors. This value, under natural light, was then compared with the same value of the sample sets projected with different lighting conditions to quantify the shifting behavior of this value.

To acquire L*, a*, and b* values for the calculation, a photo of the sample panel was taken with Iphone 12 pro camera with HEIF (High Efficiency Image File) format, which covered a wider range of color than normal JPEG (Joint Photographic Experts Group) format. The photo was then adjusted for white balance in Adobe Lightroom Classic to correct its color distortion which might have been caused by shifting ambient lighting or a camera lens. After the adjustment, each color was measured the L*, a*, and b* values in Adobe Photoshop. (Fig 4.5) Table 4.1 provides the data for each color.

![Image showing the calculation of Delta E](Image: Zachary Schuessler)

\[
\Delta E_{ab}^* = \sqrt{(L_2^* - L_1^*)^2 + (a_2^* - a_1^*)^2 + (b_2^* - b_1^*)^2}
\]

![Figure 4.5: After adjusting the white balance, each color was measured the L*, a*, and b* values (in red box) by an eyedropper tool in Photoshop](Image: Preme Chaiyatham)

<table>
<thead>
<tr>
<th>Natural Light</th>
<th>Sample Number</th>
<th>L*</th>
<th>a*</th>
<th>b*</th>
<th>ΔE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural Light</td>
<td>1 A</td>
<td>74</td>
<td>7</td>
<td>32</td>
<td>3.32</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>71</td>
<td>6</td>
<td>31</td>
<td></td>
</tr>
<tr>
<td>Natural Light</td>
<td>2 A</td>
<td>61</td>
<td>16</td>
<td>12</td>
<td>4.69</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>64</td>
<td>13</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>Natural Light</td>
<td>3 A</td>
<td>66</td>
<td>-5</td>
<td>-28</td>
<td>3.00</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>63</td>
<td>-7</td>
<td>-27</td>
<td></td>
</tr>
</tbody>
</table>
Table 4.1: A table showing L*, a*, b*, and ΔE value for samples under natural light.

The value of delta E can be translated in relation to the perception of human eyes in this range described below. This scale varies in research. However, for this thesis, the data below is used.4

- 0<ΔE < 1- observer does not notice the difference,
- 1<ΔE < 2- only experienced observer can notice the difference
- 2<ΔE < 3.5- inexperienced observer also notices the difference,
- 3.5<ΔE < 5- clear difference in color is noticed,
- 5<ΔE- observer notices two different colors.

To measure the shifting color effect of the sample under different light (metamerism), six lighting conditions were projected onto the sample sets with Optoma GT1090HDR 1080p DLP Laser Projector. These lights were in primary and secondary light color which included red, green, blue, yellow, cyan, and magenta. They were chosen to cover the light color wheel as much as possible and to provide an extreme example for this experiment. The colors were generated in Adobe Photoshop by inputting the L*, a*, and b* values of each color in the program. Photos of the sample sets under each lighting condition were captured and measured for its L*, a*, b*, and delta E value using the same method under natural light.

Result

1. Red Light

<table>
<thead>
<tr>
<th>Red Light</th>
<th>Sample Number</th>
<th>L*</th>
<th>a*</th>
<th>b*</th>
<th>ΔE</th>
<th>ΔE under Natural Light</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A</td>
<td>56</td>
<td>75</td>
<td>70</td>
<td>0.00</td>
<td>3.32</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>56</td>
<td>75</td>
<td>70</td>
<td>1.00</td>
<td>4.69</td>
</tr>
<tr>
<td></td>
<td>A</td>
<td>56</td>
<td>76</td>
<td>70</td>
<td>1.73</td>
<td>3.00</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>56</td>
<td>75</td>
<td>64</td>
<td>1.73</td>
<td>3.00</td>
</tr>
</tbody>
</table>

The delta E values of the samples were decreased under red light, compared to under natural light. Sample no. 1, 2, and 7 delta E values were equal or less than 1 which meant that the two colors looked similar. Despite the fact that other pairs of samples had higher delta E, they still appear similar to unaided eyes to each other.

2. Green Light

<table>
<thead>
<tr>
<th>Green</th>
<th>Sample Number</th>
<th>L'</th>
<th>a'</th>
<th>b'</th>
<th>ΔE</th>
<th>ΔE under Natural Light</th>
</tr>
</thead>
<tbody>
<tr>
<td>Green</td>
<td>1</td>
<td>A</td>
<td>77</td>
<td>-71</td>
<td>72</td>
<td>1.73</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>78</td>
<td>-72</td>
<td>73</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Green</td>
<td>2</td>
<td>A</td>
<td>74</td>
<td>-67</td>
<td>64</td>
<td>1.41</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>73</td>
<td>-67</td>
<td>63</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Green</td>
<td>3</td>
<td>A</td>
<td>78</td>
<td>-64</td>
<td>35</td>
<td>5.39</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>76</td>
<td>-64</td>
<td>40</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Green</td>
<td>4</td>
<td>A</td>
<td>71</td>
<td>-62</td>
<td>46</td>
<td>6.40</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>72</td>
<td>-64</td>
<td>51</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Green</td>
<td>5</td>
<td>A</td>
<td>70</td>
<td>-64</td>
<td>59</td>
<td>1.00</td>
</tr>
</tbody>
</table>
Table 4.3: A table showing L*, a*, b*, and ΔE value for samples under green light.

<table>
<thead>
<tr>
<th>Blue</th>
<th>Sample Number</th>
<th>L*</th>
<th>a*</th>
<th>b*</th>
<th>ΔE</th>
<th>ΔE under Natural Light</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1 A</td>
<td>42</td>
<td>21</td>
<td>-75</td>
<td>1.41</td>
<td>3.32</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>42</td>
<td>20</td>
<td>-74</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2 A</td>
<td>39</td>
<td>29</td>
<td>-83</td>
<td>6.40</td>
<td>4.69</td>
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<td></td>
<td>B</td>
<td>39</td>
<td>33</td>
<td>-88</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>3 A</td>
<td>47</td>
<td>22</td>
<td>-82</td>
<td>4.36</td>
<td>3.00</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>46</td>
<td>25</td>
<td>-85</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>4 A</td>
<td>46</td>
<td>25</td>
<td>-85</td>
<td>20.02</td>
<td>4.24</td>
</tr>
<tr>
<td></td>
<td>B</td>
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<td>41</td>
<td>-94</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>5 A</td>
<td>42</td>
<td>15</td>
<td>-69</td>
<td>7.87</td>
<td>5.83</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>41</td>
<td>20</td>
<td>-75</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>6 A</td>
<td>33</td>
<td>38</td>
<td>-79</td>
<td>3.32</td>
<td>6.16</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>34</td>
<td>35</td>
<td>-78</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>7 A</td>
<td>40</td>
<td>20</td>
<td>-73</td>
<td>2.83</td>
<td>4.36</td>
</tr>
</tbody>
</table>

Figure 4.7: Samples under green light
Image: Preme Chaiyatham

Under green light, all samples had lower delta E values, in relation to the value under natural light, except sample number 3 and 4 in which the sample no. 3B and 4B appeared to be slightly darker than its counterparts to unaided eyes.

3. Blue Light
Table 4.4: A table showing $L^*$, $a^*$, $b^*$, and $\Delta E$ value for samples under blue light.

<p>| | | | | | | |</p>
<table>
<thead>
<tr>
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<th></th>
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<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
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<td>85</td>
<td>-1</td>
<td>85</td>
<td>6.71</td>
<td>3.32</td>
</tr>
<tr>
<td></td>
<td>B</td>
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<td>-6</td>
<td>87</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>A</td>
<td>85</td>
<td>0</td>
<td>74</td>
<td>1.00</td>
<td>4.69</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>85</td>
<td>0</td>
<td>75</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>A</td>
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<td>-34</td>
<td>38</td>
<td>6.32</td>
<td>3.00</td>
</tr>
<tr>
<td></td>
<td>B</td>
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<td>-32</td>
<td>44</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>A</td>
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<td>54</td>
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<td>5</td>
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<td>71</td>
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<td>5.83</td>
</tr>
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<td></td>
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</tr>
<tr>
<td>6</td>
<td>A</td>
<td>70</td>
<td>40</td>
<td>76</td>
<td>6.08</td>
<td>6.16</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>71</td>
<td>34</td>
<td>76</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>A</td>
<td>85</td>
<td>2</td>
<td>85</td>
<td>3.74</td>
<td>4.36</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>87</td>
<td>-1</td>
<td>86</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 4.5: A table showing $L^*$, $a^*$, $b^*$, and $\Delta E$ value for samples under yellow light.

Figure 4.8: Samples under blue light
   Image: Preme Chaiyatham

Under blue light, four samples appeared to have higher delta E values compared to the values under natural light. This increased difference was evident, for example, in sample no. 3 and 4 where sample no. 3B and 4B were darker than their pair to unaided eyes.

4. Yellow Light
Samples under yellow light had four lower and three higher delta E values compared to those under natural light. While most of the samples appeared to be similar to the unaided eyes, sample number 1 and 4 were noticeably different. With the highest delta E values under this light, sample no. 1A looked darker than 1B and sample no. 4A appeared to be less saturated than sample 4B.

5. Cyan Light

<table>
<thead>
<tr>
<th>Cyan</th>
<th>Sample Number</th>
<th>L'</th>
<th>a'</th>
<th>b'</th>
<th>ΔE</th>
<th>ΔE under Natural Light</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1</td>
<td>74</td>
<td>-41</td>
<td>-3</td>
<td>5.10</td>
<td>3.32</td>
</tr>
<tr>
<td>B</td>
<td>75</td>
<td>-45</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>2</td>
<td>68</td>
<td>-31</td>
<td>-26</td>
<td>2.45</td>
<td>4.69</td>
</tr>
<tr>
<td>B</td>
<td>69</td>
<td>-30</td>
<td>-28</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>3</td>
<td>64</td>
<td>-16</td>
<td>-48</td>
<td>6.00</td>
<td>3.00</td>
</tr>
<tr>
<td>B</td>
<td>68</td>
<td>-20</td>
<td>-46</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>67</td>
<td>-22</td>
<td>-41</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>5</td>
<td>66</td>
<td>-40</td>
<td>-20</td>
<td>4.12</td>
<td>5.83</td>
</tr>
<tr>
<td>B</td>
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<td>A</td>
<td>6</td>
<td>60</td>
<td>-3</td>
<td>-17</td>
<td>3.74</td>
<td>6.16</td>
</tr>
<tr>
<td>B</td>
<td>63</td>
<td>-4</td>
<td>-19</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>7</td>
<td>73</td>
<td>-43</td>
<td>4</td>
<td>4.12</td>
<td>4.36</td>
</tr>
<tr>
<td>B</td>
<td>74</td>
<td>-43</td>
<td>8</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 4.6: A table showing L’, a’, b’, and ΔE value for samples under cyan light.
Under cyan light, four samples had lower delta E values compared to the value under natural light, while three samples had higher values.

### 6. Magenta Light

<table>
<thead>
<tr>
<th>Sample Number</th>
<th>L’</th>
<th>a’</th>
<th>b’</th>
<th>ΔE</th>
<th>ΔE under Natural Light</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 A</td>
<td>65</td>
<td>72</td>
<td>-32</td>
<td>1.73</td>
<td>3.32</td>
</tr>
<tr>
<td>1 B</td>
<td>66</td>
<td>71</td>
<td>-33</td>
<td>1.00</td>
<td>4.69</td>
</tr>
<tr>
<td>2 A</td>
<td>65</td>
<td>75</td>
<td>-49</td>
<td>5.39</td>
<td>3.00</td>
</tr>
<tr>
<td>2 B</td>
<td>65</td>
<td>74</td>
<td>-49</td>
<td>4.69</td>
<td>4.24</td>
</tr>
<tr>
<td>3 A</td>
<td>65</td>
<td>37</td>
<td>-54</td>
<td>14.49</td>
<td>5.83</td>
</tr>
<tr>
<td>3 B</td>
<td>67</td>
<td>40</td>
<td>-50</td>
<td>14.49</td>
<td>6.16</td>
</tr>
<tr>
<td>4 A</td>
<td>55</td>
<td>63</td>
<td>-64</td>
<td>8.31</td>
<td>6.16</td>
</tr>
<tr>
<td>4 B</td>
<td>60</td>
<td>59</td>
<td>-51</td>
<td>8.31</td>
<td>4.36</td>
</tr>
</tbody>
</table>

Table 4.7: A table showing L’, a’, b’, and ΔE value for samples under magenta light.
Under magenta light, four samples had decreased delta E values. Sample no. 4 had the highest change for this value. The difference could be perceived with unaided eyes.

Conclusion

Under every lighting condition in this experiment, the delta E values have shifted compared to the same value under natural light. While a few samples had drastically altered delta E values, most of them shifted slightly. The results showed that metameric pairs did act differently under different lights. However, the level of dissimilarity between each metameric pair was miniscule to unaided eyes.

This experiment informed us that the color calibration of the projection mapping can be done off-site. The projection mapping technologists can perform the initial calibration on a mockup, which reduces the time and cost for traveling to the site to do this calibration. However, the geometric calibration, a process of aligning the content shape to the projected surface, still needs to be done on-site in relation to the location of the installed projector. Moreover, lighting conditions could be different on-site which may affect the accuracy of the color. Thus, the final adjustment of color still needs to be conducted on-site.

The colors in this experiment were hand-mixed with artist’s pigments purchased from an art store. Further experiment on architectural paints may be needed to get results on pigments used in buildings. Moreover, the projector used was a laser projector with the brightness of 4200 lumen. The result of colors may be different in other models of projector.

One finding that was interesting and led to the next experiment was the ability of projection mapping to change one color to another. In the photo below (figure 4.12), every color was altered into various shades of blue under this intense blue light. To what extent can we alter colored surfaces using projection mapping?
B. Experiment 2

The second experiment followed and complimented the findings from the first one. The first experiment proved that one color could be altered to another through colored projected light. However, according to the literature review, the ability of the projected light to alter color has not been evaluated in existing literature (in terms of value and chroma). Some literature mentioned this ability, but it was done on lighter colors. Some studies mentioned that the effect on darker surfaces was one of the limitations of this technique. As a result of this gap in knowledge, this experiment was tested to determine the capacity of projection mapping to change colors from one to another in relation to the color’s value and chroma. Does the value and chroma affect the ability of projection mapping color accuracy? To what extent does it affect the capability of projection mapping to change color from one to another?

Methodology

The experiment was conducted on two sets of colors that varied in value and chroma. The color system employed was the Munsell color system which is systemized in terms of hue, value, and chroma. Hue defines colors (R=red, YR=yellow+red, Y=yellow, etc.) Value describes the lightness of the color where 0 is the absolute black and 10 is absolute white. The last value is chroma which defines the intensity of colors where 0 is neutral and 12 is the most intense. This experiment was divided into two settings: the Value Base Setup and the Chroma Base Setup.

First Setup: Value Base Setup

The first set up was to test the effects on a value scale. Nine gray colors varying in value from N1 to N9 in the Munsell Color System, where N1 is the blackest and N9 is the whitest, were each printed onto a roll of lightweight bond paper, 1’ by 1’ in dimension, by a laser printer at the Output Shop at Graduate School of Architecture, Planning and Preservation. Each sample was attached to a wall in a grid pattern. These samples were referred as base color N1 to base color N9 in this experiment. Figure 4.13 shows the set up of this experiment.

---

To test the ability to alter the color, a set of colors was chosen to be a target to adjust the base colors to, with the projected light. These targeted colors were categorized into three types. The first type was intense colors which included 10GY 6/12, 7.5Y 9/12, 10R 5/12, and 5PB 6/14. The second type was black since it provided the darkest example for the experiment. The last type was less saturated color with lower chroma value because it was a type of color likely to be found in historic spaces. The color employed was 2.5Y 2/2. Figure 4.14 illustrates the targeted colors employed in this experiment. The targeted colors were printed on a paper with the same setup mentioned above.

To alter the base colors N1 to N9 to the targeted colors by using projected light from the projector, the L’a’b’ color systems in Adobe Photoshop were used to generate the compensated colored light, which had the ability to alter our color perception of the base colors. These colors were sent to the projector and projected onto the base colors. The projector used in this experiment was Optoma GT1090HDR 1080p DLP Laser Projector. To achieve results on each base color that were as close as possible to the targeted colors, the compensated colored lights were manually observed and adjusted.

This process was done by attaching the first targeted color, 10GY 6/12, to the wall next to the base colors N1 to N9 to act as a reference during this color adjustment with projected light. Nine individual squares were drawn in Adobe Photoshop. Each square was
then precisely projected onto each base color, N1 to N9. The L’, a’, and b’ values of the targeted color were put in Photoshop to color each square. With this projected colored light, each base color was altered to green color (10GY 6/12) with varied values depending on the values of the base colors. The results were captured with an Iphone 12 pro camera with HEIF (High Efficiency Image File) format. The photo was then adjusted its white balance in Adobe Lightroom Classic to correct any distorted colors caused by ambient lighting and the camera lens. To measure how different the base colors with projected light were compared to the targeted color, each square in the photo was measured the L’, a’, and b’ values in Adobe Photoshop. These values of each base color were compared to the targeted color. With this information, the L’, a’, and b’ values of each square were adjusted to compensate for the color difference. For example, if the L’ value of the base color was lower than the targeted color, this value would be increased in Photoshop to compensate for the difference. (Fig 4.15) This process was done to all three values and repeated on every base color until they achieved as close as possible to the targeted color. This process was repeated for every targeted color. For example, the L’ value of the base color N1 could not be increased more than 20 (when adjusted to the target color 10GY 6/12) even with the brightest color generated by the projector due to its darker appearance. Once the L’, a’, and b’ values were adjusted as close as possible to the targeted color, the delta E values were calculated using the same method as described in experiment 1. Table 4.8 describes the results of this setup.

**Result**

<table>
<thead>
<tr>
<th>Value Base Colors</th>
<th>L’</th>
<th>a’</th>
<th>b’</th>
<th>ΔE</th>
</tr>
</thead>
</table>

This color adjustment could be achieved to a certain degree. For example, the L’ value of the base color N1 could not be increased more than 20 (when adjusted to the target color 10GY 6/12) even with the brightest color generated by the projector due to its darker appearance. Once the L’, a’, and b’ values were adjusted as close as possible to the targeted color, the delta E values were calculated using the same method as described in experiment 1. Table 4.8 describes the results of this setup.
<table>
<thead>
<tr>
<th>Targeted Color</th>
<th>10GY 6/12</th>
<th>75</th>
<th>-45</th>
<th>60</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N9</td>
<td>82</td>
<td>-45</td>
<td>75</td>
</tr>
<tr>
<td></td>
<td>N8</td>
<td>80</td>
<td>-47</td>
<td>73</td>
</tr>
<tr>
<td></td>
<td>N7</td>
<td>73</td>
<td>-46</td>
<td>66</td>
</tr>
<tr>
<td></td>
<td>N6</td>
<td>68</td>
<td>-44</td>
<td>63</td>
</tr>
<tr>
<td></td>
<td>N5</td>
<td>58</td>
<td>-37</td>
<td>57</td>
</tr>
<tr>
<td></td>
<td>N4</td>
<td>45</td>
<td>-31</td>
<td>47</td>
</tr>
<tr>
<td></td>
<td>N3</td>
<td>32</td>
<td>-25</td>
<td>39</td>
</tr>
<tr>
<td></td>
<td>N2</td>
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<td></td>
<td>N1</td>
<td>20</td>
<td>-17</td>
<td>26</td>
</tr>
<tr>
<td>Targeted Color</td>
<td>7.5Y 9/12</td>
<td>89</td>
<td>-8</td>
<td>112</td>
</tr>
<tr>
<td></td>
<td>N9</td>
<td>87</td>
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<td>94</td>
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<tr>
<td></td>
<td>N8</td>
<td>84</td>
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<td>95</td>
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<td></td>
<td>N7</td>
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<td>-4</td>
<td>89</td>
</tr>
<tr>
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<td>N6</td>
<td>73</td>
<td>-2</td>
<td>83</td>
</tr>
<tr>
<td></td>
<td>N5</td>
<td>73</td>
<td>-2</td>
<td>83</td>
</tr>
<tr>
<td></td>
<td>N4</td>
<td>54</td>
<td>-1</td>
<td>70</td>
</tr>
<tr>
<td></td>
<td>N3</td>
<td>43</td>
<td>-2</td>
<td>59</td>
</tr>
<tr>
<td></td>
<td>N2</td>
<td>35</td>
<td>0</td>
<td>51</td>
</tr>
<tr>
<td></td>
<td>N1</td>
<td>29</td>
<td>0</td>
<td>42</td>
</tr>
<tr>
<td>Targeted Color</td>
<td>10R 5/12</td>
<td>62</td>
<td>58</td>
<td>54</td>
</tr>
<tr>
<td></td>
<td>N9</td>
<td>60</td>
<td>46</td>
<td>48</td>
</tr>
<tr>
<td></td>
<td>N8</td>
<td>60</td>
<td>48</td>
<td>50</td>
</tr>
<tr>
<td></td>
<td>N7</td>
<td>60</td>
<td>50</td>
<td>51</td>
</tr>
<tr>
<td></td>
<td>N6</td>
<td>57</td>
<td>49</td>
<td>50</td>
</tr>
<tr>
<td></td>
<td>N5</td>
<td>57</td>
<td>48</td>
<td>55</td>
</tr>
<tr>
<td></td>
<td>N4</td>
<td>39</td>
<td>33</td>
<td>53</td>
</tr>
<tr>
<td></td>
<td>N3</td>
<td>29</td>
<td>25</td>
<td>41</td>
</tr>
<tr>
<td></td>
<td>N2</td>
<td>21</td>
<td>22</td>
<td>31</td>
</tr>
<tr>
<td></td>
<td>N1</td>
<td>16</td>
<td>22</td>
<td>24</td>
</tr>
<tr>
<td>Targeted Color</td>
<td>5PB 6/14</td>
<td>52</td>
<td>13</td>
<td>-72</td>
</tr>
<tr>
<td></td>
<td>N9</td>
<td>51</td>
<td>15</td>
<td>-70</td>
</tr>
<tr>
<td></td>
<td>N8</td>
<td>53</td>
<td>8</td>
<td>-61</td>
</tr>
<tr>
<td></td>
<td>N7</td>
<td>53</td>
<td>2</td>
<td>-50</td>
</tr>
</tbody>
</table>
Table 4.8: L*a*b* and Delta E value of the targeted colors and value base colors projected with colored light.
Figure 4.16: targeted colors (the right of each photo) and value base colors projected with colored light (the left of each photo)

The first four targeted colors were saturated colors with a chroma level of 12 or above. The degree of resemblance between the base colors N1 to N9 with projected light and the targeted colors was, with unaided eyes, seen only in the higher value (lighter) colors, from N6 to N9. However, when colors with values closer to the targeted colors were examined statistically, colors with values closer to the target had a lesser delta E, as shown in the 10GY 6/12, 7.5Y 9/12, and 10R 5/12. However, the color 5PB 6/14 setup had a lower delta E in its higher value base colors (N7-N9), not in values closer to the targeted color. These findings indicated that when using projected light, target colors with values close to the base colors were simpler to attain.

For the targeted color N1, which aimed to imitate a black color, base colors with lower value, N1-N4, were more closely related to the black target color than colors with a higher value. This resulted from the fact that a projector was unable to create black. The color black represents the absence of light in projection mapping. Thus, when a dark color was projected onto a surface, the actual color of the base surface was seen. This setup also supported the first setup that the projected colors were more similar to the target colors when their base color had relatively identical values to the intended target.

For the last targeted color, 2.5Y 2/2, all delta E values were less than 10. This setup demonstrated that colors with a lower saturation level had a greater ability to be achieved using projected light.

Second Setup: Chroma Base Setup

The second setup will be called “Chroma Base Setup” to test the ability to alter the appearance of color with projected light based on the chroma scale. 5.0 YR, which is among the colors in the Munsell Color System that has the largest range of chroma, was selected to be a sample for the second test. The colors included ranges of six chroma from 5.0YR 7/2 to 5.0YR 7/12, in this experiment. The six base colors were printed onto a roll of lightweight bond paper, 1' by 1' in dimension, by a laser printer at the Output Shop at GSAPP. Each
sample was attached to a wall in a grid pattern. Figure 4.17 shows the set up of this experiment.

Figure 4.17: Chroma base colors printed on papers and attached to a wall for projection

Image: Preme Chaiyatham

These six base colors were adjusted to the same targeted colors with the same setting and processes as the Value Base Setup. Table 4.9 provides the results of this setup.

<table>
<thead>
<tr>
<th>Targeted Color</th>
<th>L'</th>
<th>a'</th>
<th>b'</th>
<th>ΔE</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>10GY 6/12</strong></td>
<td>75</td>
<td>-45</td>
<td>60</td>
<td></td>
</tr>
<tr>
<td>5.0YR 7/2</td>
<td>57</td>
<td>-35</td>
<td>53</td>
<td>21.75</td>
</tr>
<tr>
<td>5.0YR 7/4</td>
<td>57</td>
<td>-32</td>
<td>59</td>
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<tr>
<td>5.0YR 7/6</td>
<td>55</td>
<td>-27</td>
<td>61</td>
<td>26.93</td>
</tr>
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<td>5.0YR 7/8</td>
<td>57</td>
<td>-22</td>
<td>66</td>
<td>29.82</td>
</tr>
<tr>
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<td>-19</td>
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<tr>
<td>5.0YR 7/12</td>
<td>53</td>
<td>-15</td>
<td>69</td>
<td>38.28</td>
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<td><strong>7.5Y 9/12</strong></td>
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<td>-8</td>
<td>112</td>
<td></td>
</tr>
<tr>
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<td><strong>10R 5/12</strong></td>
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<td>58</td>
<td>54</td>
<td></td>
</tr>
<tr>
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<td>5.0YR 7/4</td>
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<td>Targeted Color</td>
<td>L</td>
<td>a</td>
<td>b</td>
<td>(\Delta E)</td>
</tr>
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<td>----------------</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>-----------</td>
</tr>
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<td>13</td>
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<table>
<thead>
<tr>
<th>Projected Colored Light on Sample Colors</th>
<th>L</th>
<th>a</th>
<th>b</th>
<th>(\Delta E)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.0YR 7/2</td>
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<td>-42</td>
<td>30.82</td>
</tr>
<tr>
<td>5.0YR 7/4</td>
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<td>4</td>
<td>-24</td>
<td>48.84</td>
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Table 4.9: L’a’b’ and Delta E value of the targeted colors and chroma base colors projected with colored light.
When it was color a black
Setups when both were
mapping than more saturated colors, even when the base colors were highly saturated. This
might be because the base color was 5.0 YR, which had an orange and red tone to it. Moreover, delta E
levels were larger on the high chroma base colors. This revealed that utilizing projection mapping, highly
saturated colors could not be made more comparable to the highly saturated target colors.

The fifth targeted color attempted to convert the base colors to a black color. The calculation
revealed that less saturated colors had a smaller delta E value, but more intense colors had a larger
value. With unassisted vision, more saturated colors retained remnants of their underlying hue
(orange), but less saturated colors appeared gray. This setup corroborated the previous, as less saturated
colors were more likely to be closely related to the target color than more saturated colors.

The last targeted color was a less saturated color. This calibration produced the experiment’s
lowest delta E value. On colors with chroma less than or equal to 6, the delta E values were less than
10. Except for the color with a chroma of 12, all other hues had a delta E more than 10 but less than
20. These findings revealed that less saturated colors were more likely to be generated using
projection mapping than more saturated colors even when the base colors were intense in color.

4.1.A.3 Conclusion

This experiment showed how base colors with different levels of value and chroma could be
radiometrically calibrated to the target colors using projection mapping. As seen in the Value Base Setup,
the projected colors were more similar to the target colors when their base color had relatively
identical values to the targeted color. Moreover, regardless of its value, base colors could be closely altered
to the targeted color with less chroma.

The Chroma Base Setup demonstrated that strongly saturated base colors were less likely to be
made more similar to the targeted colors. Additionally, it was consistent with the Value Base Setup in
that less saturated colors were more likely to be created by projection mapping than more saturated
colors, even when the base colors were highly saturated.

Additionally, both Setups were also consistent when black was used as its targeted color. When a
black color was projected onto the base colors, it was the base colors itself
that were perceived with unaided eyes. This might be due to the fact that the projector generated a black color by using less intense light or, in certain cases, an absence of light.

These findings demonstrate the capacities and limitations of this technique. While projection mapping has great potential to alter the appearance of the surroundings, when considering using it as a part of the interpretation in a site, it is important to take into account the value and chroma levels of both the base colors of the surface and the color of the contents being projected onto it. This step is crucial to the success of the accuracy of the colors and should be closely examined early on in the project.

The colors were printed onto a roll of lightweight bond paper with a laser printer at the Output Shop at GSAPP. Due to the limitation of the printer to create accurate colors, the printed colors were slightly different from the Munsell color cards. However, they still showed the gradation of value and chroma which was the purpose of this experiment.

4.2 On-Site Experiment

This in-situ experiment sought to evaluate projection mapping installation as an interpretative tool in a house museum in order to assist in establishing the guideline in the following chapter. The workflow which derived from precedent applications in chapter 3, as well as the limitations and input from personnel and specialists, were the key sources of information for the guideline. The application is designed to address the following primary questions: how can projection mapping be integrated into house museums? To what extent can it improve interpretation and help visitors gain a better understanding of the site? And what considerations should be made from an operational standpoint?

The application was set up in the Vail House at Historic Speedwell in Morristown, New Jersey. Projection mapping was used to visualize the historic wall finishes of the stairwell inside the museum.

The Vail House Historical Background

The Vail House is located on Historic Speedwell’s site in Morristown, New Jersey. The main mansion, which was erected in the latter part of the eighteenth century by Thomas Kinney, a notable, powerful, and wealthy man, was originally known as the Kinney House. In 1830, Stephen Vail bought the structure. He was a businessman who was always experimenting with, and adding more technologically sophisticated construction technologies, into his homes.7 The building functioned as his laboratory from the moment he moved in. The invention and successful testing of the telegraph, which Vail sponsored, was one of the most noteworthy events that occurred in the home. Thus, the events surrounding the construction of the telegraph in 1838 established the entire site’s qualifying for the State and National Registers of Historic Places.

The house began as a late Georgian-style mansion with a formal five-bay western wing and a less formal eastern wing for practical uses. It was updated to a Greek Revival design prior to the major alteration work in the 1840s, which included a new foundation and the relocation of the structure to its current location. After 1844, when Stephen Vail moved in, the house was regularly remodeled, although on a small scale. The Lidgerwood family, who occupied the house following Vail, continued to make changes in the late nineteenth and early twentieth centuries. By the 1960s when the house was neglected and deteriorating, Historic Speedwell, Inc. purchased it. They began an endeavor to interpret it to

the time of Stephen Vail, which was the 1840s. The most prominent interior modifications were performed in the 1970s, with project money provided by the Morristown Junior League. Despite certain late nineteenth and early twentieth century components, the house gives the appearance of the mid-nineteenth century house, which aligns with the period of interpretation, 1844 to 1864, during the renovations and residency of Stephen Vail.  

8 Eclectic Architecture, 7–19.
10 Ibid.

Methodology

The interpretative applications of projection mapping in house museums can come in many different forms and settings. Consultation with a curator at the Vail House was a critical initial step in determining the most appropriate use of this technique. This interaction with museum staff was essential since it ensured that the usage of projection mapping was consistent with the primary interpretation of the site. Prior to the discussion, historical context and a paint study from Eclectic Architecture’s historic building report on the Vail House were studied. The review aided in the subsequent discussion with the curator on the site.

The interior finishes were one feature that was constantly updated. One of the most intriguing internal elements of the home was the painting of a faux ashlar sandstone pattern that was the original paint on the unpainted Georgian style wall previous to Vail’s remodeling. Vail introduced Greek Revival style to his home during the 1840s renovation on the exterior. A classical portico was erected to the south, and the house’s siding was altered to a flush board, which was a high-style treatment for frame houses in the Greek Revival era in an attempt to create a cut stone appearance.
The exterior cut stone feature was brought into the stair hall on both the ground and second floors in a form of faux painting technique. This kind of treatment was a popular method with the new romantic styles of the Greek Revival and Italianate Revival styles. This finish in the Vail House is a fine example of a mid-nineteenth century wall decoration that is one of the few existing examples of original faux decoration of its kind. The time when this painting was done was not established. However, Vail's diary accounts, the aesthetic of the 1840s time period, and the alteration from unpainted Georgian walls supported the use of this technique as a part of the period of interpretation. (Figure: 4.20)

Figure 4.20: The faux masonry finish
Image: Preme Chaiyatham

The original faux painting finish is visible in two locations which include an area behind a radiator on the first floor and the southwest wall on the second floor. The area on the second floor is the most complete since it was not overpainted but was concealed behind an elevator which was removed in 1974. Although it shows white marks in areas with cracks and holes, the overall condition of the finish is still intact. To confirm that the technique was done throughout the stair hall, two exposure windows (a removal of overpaints to reveal the original finish underneath) on a southwest wall on the first floor and on a stair landing were done by J. Christopher Frey of Keystone Preservation Group. These windows confirmed the existence of the finish throughout the space.

The finding of this unique finish was then discussed with the curator, who determined that it was the most appropriate interpretation to make, as it was completed during Stephen Vail's 1840s remodeling, the house's primary interpretation period. The position of the projection mapping location was unanimously chosen by the curator and the author. It was the north end wall of the house, on the stair landing, which served as a transition between the first and second floors. (Figure 4.21) Projecting an image of the original faux painting on this wall was the ideal approach for demonstrating the two floors’ interrelated features and making it highly visible to visitors on both floors. The exposure window in the bottom left corner of the wall is the only remnant of the faux painting in this area. The goal was to expand the finish to encompass the entire wall to assist in interpreting the space, which already features the original stair and millwork. Additionally, the projected image can be compared to the exposure window side by side to enable visitors to reference the actual pattern and compare the projection to the real one.

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11 Eclectic Architecture, Section IV, pg. 3–4.
After establishing the installation location, a test run for the projector was required to determine the projector’s location and to ensure that the entire wall could be covered with projected light. This was accomplished by measuring the projected wall’s dimensions with a laser measuring device and a measuring tape. A drawing of the wall was created in AutoCAD to ensure that the visualization was precise. An image of the original faux painting was crudely filled into this outline for this initial step. This image was then projected onto the wall through a projector. Carrying and moving the projector manually around the space was necessary to identify the optimal location and height for the projector. Following this process, it was determined that a space on the second level adjacent to the stair handrail was the optimum site for the projector. The projector required to be tilted in this place because the projected wall was located on a lower landing. The projected content was significantly distorted as a result of this abnormal position.

To ensure that the distortion could be corrected, initial geometric calibration was done on the hardware using the H-shape correction function that came with the hardware. The H-shape correction is a setting in a projector to rectify a keystone distortion, in which a rectangular-shaped image appears as a trapezoid shape, in the projected image. Despite a crude alignment, this preliminary adjustment showed that it was possible to align the projected content onto this wall. Figure 4.22 shows the process. The next step was to digitally visualize the final projected image in software.
To digitally visualize the faux masonry finish, a high resolution image of the existing finish on the southwest side of the second floor stair hall was taken. The image was then corrected for its white balance and perspective distortion in Adobe Lightroom. The initial outline of the wall created in AutoCAD was imported in a pdf form to Photoshop to act as an outline to fill in the masonry pattern. Using a rectangular marquee tool, polygonal lasso tool, and transform tool, each masonry unit of the base photo was selected, rotated, and reflected to fill in the outline of the projected wall. This masonry-by-masonry process of visualization ensured the random pattern of the finish to achieve the most photorealistic final image as much as possible. Figure 4.23 - 4.24 shows the process and result.
Figure 4.24: Each masonry unit was selected and rotated/ reflected to achieve the random pattern of the original finish.

Image: Preme Chaiyatham

Cracks and white marks in the photo taken were eliminated in Adobe Photoshop using a stamp tool. This resulted in a final photo for the projection mapping. Figure 4.25 shows the process.

Figure 4.25: Cracks and white marks were corrected using a stamp tool in Photoshop.

Image: Preme Chaiyatham

The final image was imported to a projection mapping software called Resolume Arena. A function called warping in this software could help adjust the geometry of the distorted content to make it perfectly align with the physical wall. To perform this calibration, the u-shaped image was divided into three parts. (Figure 4.26) Each part was manually warped using the warping tool in this software in order to align each of them to the corresponding corners on the actual wall. The warping tool was used again to adjust the distorted height of each masonry unit as can be seen in figure 4.27. Figure 4.28 shows the distorted image compared to the final appearance of the projection mapping installation.
Figure 4.26: The image was divided into 3 parts, corresponding with the U-shape geometry of the wall, to perform the warping in Resolume Arena.
Image: Preme Chaiyatham

Figure 4.27: Unwarped image (left) was processed in the software to geometrically calibrate the distortion, resulting in a warped image (right).
Image: Preme Chaiyatham
Interviewing Sessions

The setup, discussed above, helped clarify the first question of this experiment which is how projection mapping can be incorporated into a house museum. To examine other questions, an evaluation through group interviews with professionals in the preservation industry were conducted. There were two interview sessions with sixteen participants in total. Each interview lasted approximately an hour. The participants were staff of the house museum, local preservation experts from both private and government bodies, and specialists in conservation. A brief presentation on projection mapping was given to make the participants understand the technology used for this experiment. Participants had a chance to freely examine the virtual reconstruction of this faux masonry finish before the group interview. The group interview was moderated by the author and was audio-recorded with permission of the participants.

Discussion

By and large, all participants believed that this method of interpretation using projection mapping was excellent and had tremendous promise for cultural places. One participant remarked that this approach appeared to be quite cost effective, given the high expense of restoring a complete wall. Additionally, it enhanced the “wow factor” of visiting this site. The potential of this technology to transport visitors to not just one but numerous eras created an entire narrative for them. Its immersive and non-permanent nature was another common thought among the participants.

When asked to compare this method to traditional interpretation, one participant stated that seeing the original finish was one thing, but seeing the entire wall in its original form was quite another. The before and after look of the blank wall transforming into a faux-masonry finish altered their perception of the hall’s grandeur. According to Jude M. Pfister, chief of cultural resources at Morristown National Historical Park, this “offered visitors a chance to use imagination, to be part of the reconstruction almost themselves, rather than seeing the original finish. They were being challenged almost, to be part of it to suspend their sense of reality and what is not”.

Figure 4.28: Distorted image due to the tilted projector (left) and the final appearance of the installation (right).
Image: Preme Chaiyatham
Regarding its limits, the participants discussed a variety of issues. Certain individuals expressed concern over the shadow created on the wall when a person stepped in front of the projector. However, many agreed that this was not an issue because it was inherent in the technology. Additionally, the color of the projected surface was debated extensively. Darker surfaces and wallpapered walls were the primary source of concern. However, other people proposed covering a segment of those surfaces temporarily with a light-colored sheet in order to include this technique.

Surprisingly, the appearance of the hardware in the historical space of the house museum was not an issue for most of the participants. The reason behind this was that the benefit outweighed, in that regard, the cost. Furthermore, the hardware would become part of the modern elements in the space such as lighting fixtures, smoke detectors, and fire alarms. However, all agreed that it would be best to find a way to make it the least obtrusive as possible. Each organization would need to work on this to make it appropriate for their site.

Another issue of debate was the unavailability of the original finishes to be replicated. There was an uncovered piece of the original wall at the Vail House. However, in the absence of this resource, visualization may be difficult. Some noted that basing the visualization on a similar finish from other sites could be a possibility. Additionally, trade catalogs and Munsell Color Standards may be valuable resources.

Additionally, the effect of ambient light was extensively discussed. All participants expressed concerns for a well-lit room. However, several recognized that because the majority of space in a house museum would be dimmed by a blind or curtain to mitigate any photodamage caused by natural daylight, this would not be a significant concern in most situations. The issue of bright ambient light was examined in greater detail, given the majority of precedent applications were interiors. Exterior applications were limited to the evening hours only. One participant, however, acknowledged that bringing users to the site at a different time of the day was not necessarily a negative. It could be an excellent method to get experience of the place, provided that the operation staff is readily available.

In terms of operational considerations, there were some features in common. All participants would like an easy-to-use system, such as manipulating the images via an iPad. This resulted in a general consensus that the site would need to contract with an outside provider to set up and administer the system, as the majority of cultural sites lacked technical personnel. Once the system is installed, operation will be simple because it will become ingrained in the site’s routine.

Apart from these limitations, the two interview sessions generated numerous ideas for potential applications of this technique. Besides the several eras that projection mapping can show, it can also denote various elements other than finishes. The projected features included furniture, artworks, and architectural aspects. Even though these elements would be two-dimensional, they would give visitors a sense of space. This potential to enlarge the time of relevance, depict new characteristics, and enhance the site experience became an exhibition unto itself. Finally, several participants recognized this as a tool that, when compared to a plain wall, would leave a lasting impact.

Moreover, the discussion also generated a few philosophical questions about the use of this technology on cultural heritage. Why should we physically preserve the structure when we can do it digitally? Is it more environmentally friendly to restore digitally than traditionally? Can this digital platform make the site more accessible? Is the experience compromised since we use only visual perception for this interpretation? Is it more appropriate to reconstruct the heritage digitally when our current preservation guidelines discourage us to do it physically?
Conclusion

To summarize, this on-site experiment demonstrated how to integrate projection mapping as an interpretive tool for a house museum by synthesizing methods from precedent applications. The workflow utilized in this experiment aided in the clarification of necessary procedures for the use of this technique, which in turn aided in the development of the guidelines in the following chapter. Experts in the industry provided valuable insight on its application. The majority of comments were overwhelmingly positive, which sparked a discussion about implementing this technique into a house museum context. However, there were a few critical points to keep in mind when utilizing this technology. Among the most often discussed issues were the shadow and the projected surface’s conditions. The scarcity of replicable original finishes and the effect of ambient lighting were extensively discussed. Additionally, the appearance of the hardware could be altered to be less obtrusive in the room. Nonetheless, according to participants, the benefits this technology brought to the site exceeded its drawbacks and created more opportunity for the sites to expand their full story. However, with all this feedback in mind, there are several philosophical questions that still remain unanswered by this experiment and this thesis.
Chapter 5
Guidelines

In this chapter, findings found in the previous chapters are synthesized into guidelines which aim to be a practical instruction for cultural heritage professionals to consult with as a starting point for projection mapping projects. Deducted from the analysis of precedent application in chapter 3, the guidelines are divided into five parts ranging from the start of the project to the end.

Pre-Project Stage

1. The manager of cultural heritage and stakeholders should take all aspects of projection mapping seriously. They should educate themselves thoroughly about this technology in order to comprehend the implications for the site, interpretation, and visitor experience.

2. The project team should conduct research on the viability of projection mapping for the use of their intended interpretation of the site which includes
   a. The type of content being projected. The curator of the site should review this step extensively together with other experts on the cultural heritage at hand and the visual technologists to consider the possibility and suitability of the technique in relation to the content. Some interpretations are suitable to utilize projection mapping, but not all. It is prudent to consider whether or not this technique is worth incorporating into the interpretation of the sites early on in the project.
   b. The limitations of the color of the projected surface. The level of value and chroma of both projected content and surface. (See chapter 4. off-site experiment 2 for reference)
   c. The availability of space for the installation of hardware which includes enough space for the throwing distance of the projector.
   d. The level of ambient lighting conditions and ways to control it.
   e. The non-monetary cost associated with implementing this type of technology. This includes, but is not limited to, site modifications such as ambient lighting control, projector installation, and projection surface preparation. It is critical to consider how these applications will affect the visitor experience, as well as the authenticity and integrity of the site.

3. The project team should conduct the feasibility study of this technique which includes
   a. Hardware and software
i. It is vital to evaluate hardware that is compatible with the available space. Brightness, throw ratio, and resolution are the major criteria to consider.

ii. By 2022, several manufacturers will have phased out traditional lamp projectors in favor of laser technology. This results in a longer lamp life for the projector. However, the projector's price will increase as well.

iii. The hardware cost does not include the projector alone. Additionally, it should include the cost of wiring, mounting equipment, and a laptop or media player for image control.

iv. While many developers offer a free version of the software, there are some restrictions on its use. It is advised that a subscription to the software is purchased. Typically, it is a yearly subscription.

b. Installation

i. Consider the practicality of the installation location for the projector. Typically, they are mounted on the ceiling to facilitate visitors' circulation across the space. Scaffoldings or the removal of floor boards on the upper level may be required in some situations during the installation.

ii. The primary wiring requirements include connecting the projector's power cord, the HDMI or LAN cord to the laptop or media player, and the audio cord to the speakers (if any).

iii. Numerous control options are available. While control panels and motion sensors require installation of its hardware inside the space, a wireless controller via a tablet does not.

c. Maintenance

i. Lamps used in projectors may need to be replaced. The duration of this maintenance is determined by the lamp life (as specified in the projector's specification) and the number of hours of operation. Additionally, this type of lamp requires a cool down period after switching off, which means that the projector must be powered for a period of time after turning off.

ii. The lamp life of laser technology is far longer than that of a conventional lamp. Additionally, it does not require a cool down period after switching off. As a result, it is suggested.

d. Outsource personnel for both heritage professionals and projection mapping technologists.

i. Appropriate content for projection mapping as an interpretative tool requires close collaboration with field experts, including cultural and architectural heritage specialists, as well as audiovisual specialists. If the institution lacks these types of in-house professionals, it may be necessary to get into a contract with outsource services.

e. Operation procedure and viability
i. The operation of projection mapping should be considered since it will become ingrained in the site’s routine. This includes, but is not limited to, powering on and off the hardware, operating it, and maintaining it.

ii. Staff training to operate the system may be required. This service should be given by the retained audio-visual technologists responsible for the installation of the projection mapping.

f. Financial sources and plans should be readily available. As can be seen in precedent applications in chapter 3, multiple sources from both private and government bodies should be consulted.

4. Although the cost for the hardware and software for projection mapping has been more accessible in recent years, as can be seen from the precedent application, the expense for the visualization and implementation by outsource organizations can be costly. This factor needs to be taken into serious consideration before embarking on the project.

5. The project team needs to evaluate the authenticity and use of projection mapping for their interpretation using the parameter deducted from the Nara Document on Authenticity explained in chapter 2 and exemplified in chapter 3. This is to ensure that the interpretation has materials and abilities to transmit the authenticity of the site before starting the project. This type of evaluation should be revisited in every process throughout the project.

6. Case study tours may be conducted to open more avenues for the incorporation of this technique and possible contents that can be integrated to the project.

Research

1. Extensive research needs to be conducted to generate the most relevant, accurate, and interesting content for the interpretation. Experts on relevant topics of the site and interpretation should be retained by the project manager.

2. The content needs to be developed in tandem with the selection of the location of the projection mapping installation which dictates the basis and the presentation of the content.

3. The research process requires a close collaboration of the heritage professionals, institutions staff, and technologists for the successful completion.

4. It is an iterative procedure during the research stage. As a result, considerable time should be spent evaluating the materials’ meanings, artistic value, appropriateness for projection mapping, educational value for visitors, and alignment with the site’s interpretation.

5. The amount of information that is provided should be carefully examined. In some circumstances, extensive exposure of multiple subjects may not be suited for this type of technology, as demonstrated by the Thomas Cole House project, where the storyline was shortened to match the technique. However, the utilization of limited range and superficial content may preclude this application from fully exploiting its
potential. Thus, a careful balance between information and application should be maintained.

6. Incorporating information sourced from outside the museum or organization may need additional effort, time, and resources to address communication and copyright concerns. As demonstrated by the Thomas Cole House project, which required the acquisition of high-resolution replicas of the artist's works from external organizations.

7. Research on different hardware needs to be done. Specification, suitability for the available space, cost, and maintenance should be the primary criteria to consider. Multiple techniques should be considered during this process, including edge blanding to cover larger space and stacking to achieve higher brightness, since it will directly affect the cost, location of application, and type of projector. This process can be consulted with representatives from different manufacturers for comparison.

8. The type of the final presentation should be carefully researched, designed, and developed in this process for the successful exhibition. For example, the Harvard Murals project turned off the projectors at 4 pm every day. This did not allow the visitors to experience both versions of the Murals but it also served as an attraction which drew a large crowd to the exhibition. Accompanying texts, signages, or tour guides should be developed concurrently with the content.

9. It is necessary to closely consult the evaluation on authenticity throughout the research process to ensure that the project conveys the true perception of the cultural heritage at hand.

Visualization

1. The process of visualizing the content is iterative, requiring back and forth communication with the research stage to determine the optimum content and level of visualization for the project.

2. The cultural heritage institution's team should collaborate closely with the visual technology team to ensure that the visualized contents are consistent with the site's interpretation.

3. The digital visualization of the projected contents can be carried out concurrently with the research. Once the preliminary content is established, the visual technologists can begin creating draft versions of the content. This step should be taken early in the process to ensure that the contents, visualization, hardware, and location of the projector are all compatible.

4. The team should carefully measure the projected surfaces' dimensions. Additionally, the dimensions of the space should be measured in order to determine the projector's location in relation to the throw ratio. This is to ensure that technologists are working with an exact dimension of the surface and space.

5. For the purpose of digitally visualizing architectural finishes, the original finishes on-site might serve as a starting point. However, in some instances, the original finishes may be unavailable. In these situations, comparable or equivalent finishes on
other historic sites can serve as a useful resource. Additionally, color codes contained in available paint analysis or historic structure reports, such as the Munsell Color System or commercial codes, might be reviewed throughout this process.

6. The digital visualization of some narrative materials, such as stories of owners, places, or works, might benefit from archives, primary, and secondary literature. In some instances, the contents must be extracted from sources protected by copyright. To determine the most appropriate source for this process, the team should confer with the research and project teams.

7. The visualization of the projected contents does not include only those that are involved in the projection mapping itself. The whole team involved in the presentation of the interpretation at hand should extensively collaborate with one another. This includes, but is not limited to, the projection mapping technologists, the audio-visual technologists, lighting designers, graphic designers, cultural heritage experts, and the site's staff.

8. Several suppliers rent the hardware required for projection mapping. This also applies to software by developers. As a result, these two components can be rented throughout the visualization process, or even the research process, in order to limit the cost and save money on purchasing them during the calibration phase, as research and visualization might take a long time.

9. A method to control the projection mapping should be discussed extensively in this process as the technologists have to integrate it into their workflow. For example, using a motion sensor to trigger the projection mapping is different from writing a code to control it via a tablet.

10. More complex projected surfaces may need additional procedures such as 3D scanning to achieve the topography and geometry of the projected surface as can be seen in the Sant Climent de Taull project which needed to deal with the domed apse. Moreover, complex surfaces may require edge blending technique which necessitates the use of multiple projectors to cover the surface seamlessly. Thus, the location of each projector should be carefully placed.

11. Throughout this procedure, a review of the visualization's accuracy should be undertaken to guarantee that the outcome is authentic and conveys the real perspective of the site.

Calibration and Installation

1. Geometric calibration can be performed remotely by the creation of a mockup of the projected surface. This can be accomplished by printing a full-scale replica of the projected surface, simulating the space's actual dimensions, and positioning the projector in a spot identical to the one on-site.

2. While the geometric calibration can be performed remotely, the final calibration must be performed on-site. The process takes time and resources. Travel and accommodation expenses should be prepared. The availability of pertinent teams...
should be carefully planned including, but not limited to, the visual technology team, contractors, and installation teams.

3. Radiometric (color) calibration can also be performed off-site by printing or painting a colored replica of the projected surface. To guarantee that the colors match the on-site surface, the Munsell Color system or a commercial color code derived from paint analysis or historic structural records might be employed.

4. As with the geometric calibration, the final color calibration must be performed on-site in the presence of ambient and artificial light.

5. The installation of the hardware such as the projector, control panel, wiring, and audio system would be done with great care. A consultation with preservation architects and engineers may be necessary.

6. The incorporation of the hardware into the historical atmosphere of the site may require physical intervention so that the appearance of the hardware can be less disruptive. For example, the Sant Climent de Taull project designed and installed a new platform for the altar and a set of metal platforms on the side aisles so that the projectors could be concealed from the visitors' view.

7. The calibration and installation should be closely monitored to ensure that the end result complies with the authenticity of the site.

Application and Evaluation

1. Following installation, the site manager and stakeholders should conduct a thorough run-through of the system and evaluate it. This enables the application to be consistent with the site's interpretation and to optimize the visitor experience. This includes, but is not limited to, familiarizing staff with the system and testing the system to ensure that it functions properly.

2. Speculated contents or contents without physical evidence should be notified and clarified to the visitors to make them aware of the authenticity of the interpretation. Projection mapping has the potential to recreate missing elements or features from the site's history in order to interpret it and engage visitors. However, there are times when physical evidence is lacking and its visualization is based on research. Visitors should be aware of it in this case to ensure a true perception of the site.

3. A post-installation evaluation is critical for developing and incorporating this technology into the preservation industry. It is critical to conduct an evaluation among cultural heritage experts and production teams in order to identify opportunities for development.

4. Public evaluations are critical for gathering feedback from the public that will aid in altering the content or building future projects.

5. The project should be monitored overtime to evaluate the outcome and further development.

6. Monitoring and maintenance should be performed on both the hardware and the system. Outsourced personnel may be retained to maintain the system's functioning.
Future Research

Although this thesis covers several key projects using projection mapping for the interpretation of cultural heritage, they are still limited to the interiors. Further research on the capacities and limitations of the application of this technique on the exterior needs to be conducted. Furthermore, the first off-site experiment needs to be further conducted with historic and contemporary architectural paints to see its effects on metamerism. The second off-site experiment will benefit from testing on architectural paint as base colors and diverse targeted colors in terms of values and chromas. Further tests using different projectors with more sophisticated specifications may yield different results. For example, using a projector with higher brightness may be able to eliminate some limitations on base colors with lower values.

The on-site experiment was limited to the digital restoration of an architectural finish. Further research should be done on expanded narratives such as the history of the site, stories about events and owners, and the landscape in which the site is located. With these expanded contents, further evaluation with experts and visitors should be conducted to gauge the technique’s efficacy. Lastly, philosophical questions about the use of this technique should be investigated. Why should we preserve the structure physically when we can do so digitally? Is digital restoration more ecologically friendly than traditional restoration? Is this digital platform capable of increasing the site’s accessibility? Is the experience compromised by the fact that this interpretation relies solely on visual perception? Is it more prudent to restore heritage digitally when existing preservation guidelines limit physical reconstruction?
Appendix

Artists' paints used in off-site experiment 1

<table>
<thead>
<tr>
<th>Paint Type</th>
<th>Brand and Color Code</th>
</tr>
</thead>
<tbody>
<tr>
<td>Naple yellow</td>
<td>Gamblin, PW6, PY75, PY43</td>
</tr>
<tr>
<td>Burnt Umber</td>
<td>U.S. Art Supply</td>
</tr>
<tr>
<td>Titanium white</td>
<td>U.S. Art Supply</td>
</tr>
<tr>
<td>Vermilion</td>
<td>U.S. Art Supply</td>
</tr>
<tr>
<td>Scarlet</td>
<td>U.S. Art Supply</td>
</tr>
<tr>
<td>Ultramarine</td>
<td>Winsor &amp; Newton, Winton Oil Colour, PB29</td>
</tr>
<tr>
<td>Phthalo Cyan blue</td>
<td>U.S. Art Supply</td>
</tr>
<tr>
<td>Cerulean blue</td>
<td>U.S. Art Supply</td>
</tr>
<tr>
<td>Cadmium red</td>
<td>Winsor &amp; Newton, Winton Oil Colour, PR108</td>
</tr>
<tr>
<td>Viridian green</td>
<td>U.S. Art Supply</td>
</tr>
<tr>
<td>Burnt sienna</td>
<td>U.S. Art Supply</td>
</tr>
<tr>
<td>Yellow ochre Acrylic</td>
<td>Golden Artist Colors, PY43</td>
</tr>
<tr>
<td>Titanium White Acrylic</td>
<td>Golden Artist Colors, PW6</td>
</tr>
</tbody>
</table>

Participants in the interview sessions at the Vail House

Melanie Bump, Curator of Collections and Exhibits, Division of Cultural and Environmental Resources, Morris County Park Commission
Katie Humphreys, Registrar, Division of Cultural and Environmental Resources, Morris County Park Commission
Ryan Hyman, F.M. Kirby Curator of Collections; Ann Fahey, Superintendent of Horticulture Education, Morris County Park Commission
Amy Curry, Executive Director of Morris County Historical Society
Lynn Laffey, Director of Historic and Interpretive Sites, Morris County Park Commission
James Lewis, Department Head, North Jersey History and Genealogy Center, Morristown and Morris Township Library;
Jude M. Pfister, Chief of Cultural Resources, Morristown National Historical Park
Cara De Gaudio, Education Assistant, Morris County Park Commission
Alexandra Gizzi, Historical Program Specialist, Morris County Park Commission
Catherine Allison, Education Assistant, Morris County Park Commission;
Gary Helm Darden, Associate Professor of History, Dept. Chair, Social Sciences & History, Fairleigh Dickinson University;
Abigail Belcastro, Administrative Assistant, Social Sciences & History, Fairleigh Dickinson University.
Janet Foster

Interview Questions

1. How do you think this technique will help visitors learn more about the site?
2. How is it different from traditional interpretation? Or physical restoration?
3. Do you see any pros and cons of this technique as an interpretation of architectural finishes?
4. What opportunities or other applications do you think this technology can help with at the site? For example, a fundraising tool, a communication tool between owners, conservators, researchers, and paint decorators?

5. If it was to be installed for this house museum as a part of the exhibition, it would need to be installed on the ceiling. Do you think its appearance in a historical setting like this will disrupt any experience for the visitors?

6. At Thomas Cole House, they turn all the projectors on all day during the opening hours and they trigger them by a controller or an ipad. What is your feedback on this kind of operation?

7. The technology of projectors nowadays is very advanced. While newer models like laser projector can last for more than ten years, on certain occasions, the projectors may need to be replaced. For example, the changing contents or interpretation. How would this hardware/software update and cost affect the museum in terms of fund, personnel, and other aspects?

8. Do you see any possibilities for this technique to be used in other historic sites? If you were an owner, would you incorporate this technology into your site and why?


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