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Design Guidelines for Mobile Augmented Reality Reconstruction

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Design Guidelines for Mobile Augmented Reality Reconstruction

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Statement of Authorship

Herewith I declare that I am the sole author of the submitted Master's thesis entitled:

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I have fully referenced the ideas and work of others, whether published or unpublished. Literal or analogous citations are clearly marked as such.

Munich, 9.9.2019 Peilun Yuan

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Abstract

Augmented reality provides the experience that blurs the border of the virtual and real world. As a relatively new technology, AR only became more well-known to the public since the mid-2000s. With the development of technology, AR experience can be applied to mobile devices and has been used in various fields. For the field of cultural heritage or tourism, AR can be used to display the buildings which don't exist nowadays. The users can then perceive the simulation from the AR reconstruction.

For applications for AR reconstruction, they require the match between the augmented objects and their surroundings and provides guiding function at the same time. Considering the specialty of AR reconstruction, the related research still lacks a thorough investigation and guidelines especially for it. Hence, this research aims to identify the features of AR reconstruction and propose a set of guidelines for it. A case study is conducted at the ruins of a medieval tower which was called Prinzessturm in Munich, Germany. A mobile AR application is developed with the proposed guidelines and is used for the evaluation to explore the effectiveness of the guidelines. The evaluation results show that the app with the proposed guidelines can enhance the users' understanding of the ruins with high satisfaction. The identified features of AR reconstruction and the proposed design guidelines can provide a design reference to the developers and help them in the early stage of the development.

Keywords: Mobile augmented reality, AR design guideline, cultural heritage, digital heritage

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1 Introduction

1.1 Background

Augmented reality (AR) is a rapidly growing technology, which displays virtual objects in the real world. It has already been applied to many fields, like gaming, navigation, tourism, etc. Through the superimposition of virtual objects to the physical environment, the mix of the virtual and real-world provides people a new experience of daily life. For cultural heritage, the social, historical, cultural and educational value of AR application have been explored (tom Dieck and Jung 2017). It can greatly enhance the experience especially for AR with reconstruction purpose. AR reconstruction is a kind of application which relates to tourism, cultural heritage and archaeology. The feature is to reconstruct the objects through AR technology as if they are rebuilt at the same site. AR is especially beneficial to this kind of application since most parts of the ruins are usually absent and invisible. It is hard for people to perceive how they look like in the past by just visiting the site. By means of AR, ancient buildings can be reconstructed and presented for people to appreciate the old appearance.

One of the first AR application, ARCHEOGUIDE, was introduced in the year 2000. At that time, multiple sensors and devices were needed for creating AR effects. Most of the research at that time focused on overcoming technical problems, there was little appreciation of user interface design principles in the development. The problem may result from the difficulties from the differences and fast changes in hardware capabilities and device availability (Andreas et al., 2007). In the current stage, some researches have noticed the issue and proposed some mobile AR design principles and guidelines. With the development of technology and mobile devices, AR experience is becoming more accessible and popular especially since the release of the mobile AR game Pokémon GO in 2016. Although some design principles from the aspects of user experience, interface, and heuristic evaluation have been developed, the general principles are not enough for the AR reconstruction due to its special features. In order to solve the above challenges of AR reconstruction, this thesis research tried to explore the features and propose a set of design guidelines for it.

1.2 Research Identification

The overall research goal of the thesis is to develop a set of AR design guidelines specific to AR reconstruction. First of all, the development of AR techniques and their limitations have to be understood. After developing the guidelines, it is also necessary to evaluate their effectiveness. Here come the research objectives and the corresponding questions.

Table 1-1 Research objectives and questions

Research objectives	Research questions
1. Identify the features of AR reconstruction.	• What is special to applications for AR reconstruction? • How to identify the features of AR reconstruction?
2. Integrate the mobile AR design principles from various aspects and form a new set of AR design guidelines.	• How to develop the guidelines? • What should be included within the guidelines?
3. Develop a prototype based on the proposed guidelines.	• How to develop the prototype? • How to integrate the proposed guidelines?
4. Evaluate the effectiveness of the guidelines with the prototype.	• How to design the evaluation experiment? • How helpful are the proposed design guidelines?

1.3 Thesis Structure

The thesis consists of 6 chapters. The first chapter describes the background and the purpose of the thesis research. The second chapter is about the state of art of AR technology, interaction, and visualization techniques. The third chapter states the methodology of the research and the process for forming the new design guidelines. The nowadays development of AR application for reconstruction purpose will be discussed as well. The elements which are related to AR design are discussed then the guidelines are proposed based on the summarization. The fourth chapter focuses on developing an on-site prototype which is integrated with the guidelines. It includes making the 3D model and the process of application design. The fifth chapter is about evaluating the proposed guidelines by designed experiments. It includes the process and the results of the evaluation.

The sixth chapter discusses the summary that answers the research questions and the outlook for further research.

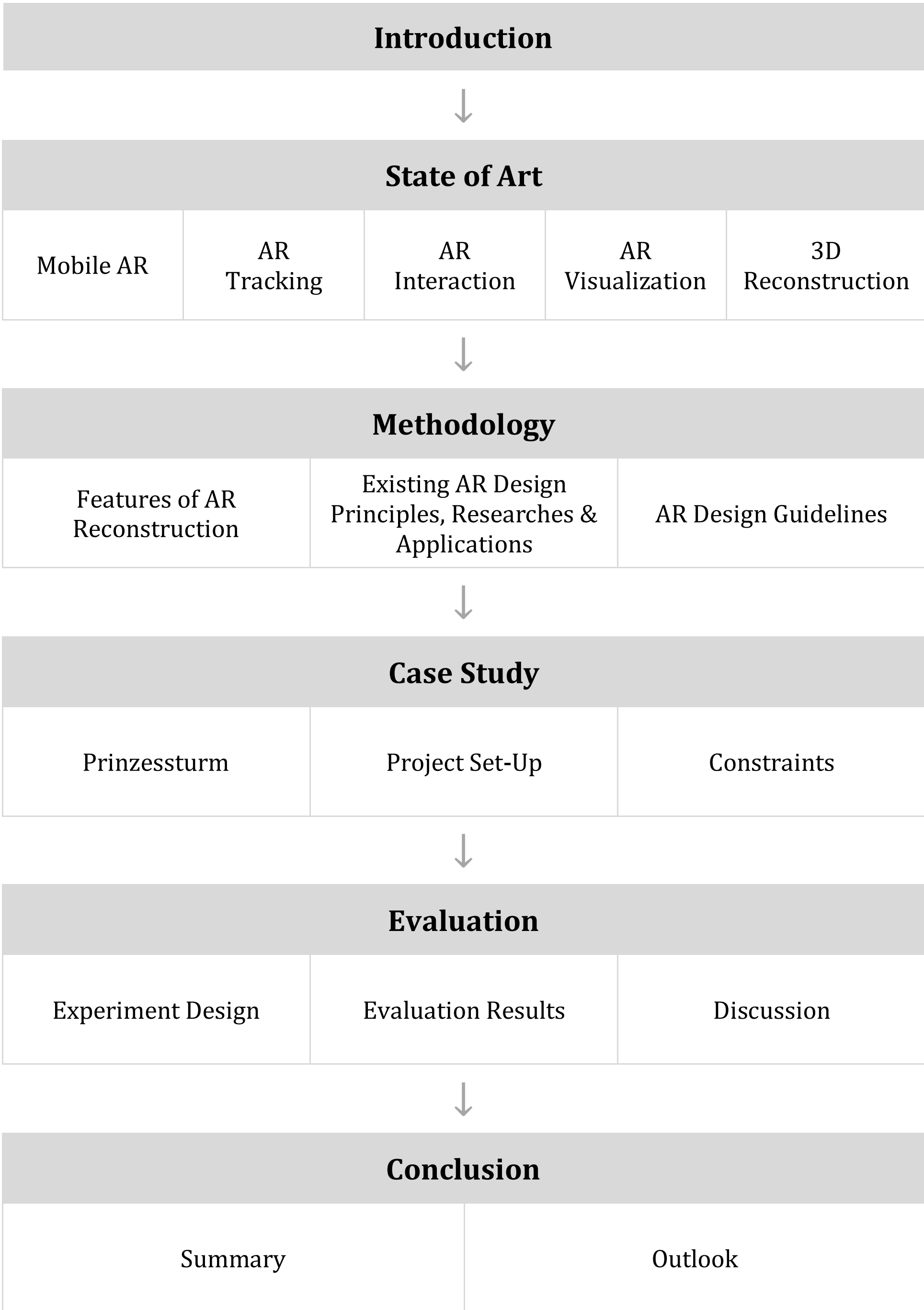


Figure 1-1 Thesis structure

2 State of Art

In this chapter, the development and the features of mobile AR are discussed from the aspects of AR tracking and registration, interaction, visualization, and 3D reconstruction. The scope of AR of this thesis research is within mobile AR. Mobile devices are more popular and prevailing in comparison with other AR devices like glasses and headsets and the development of mobile AR is also more mature. So far there are abundant resources for the research and development of mobile AR. It makes AR experience more available through smartphones and tablets.

2.1 Mobile Augmented Reality

The development of AR technology began in the 1960s. In 1994, Milgram and Kishino proposed "reality-virtuality continuum" which differentiated the technology between the continuous scale between reality and virtuality. Since then, AR has been recognized as an independent field of study. Compared to mixed reality (MR) and virtual reality (VR), augmented reality provides more realistic experiences with the mix of the virtual and real environment. However, the development of AR was still limited and remained at the phase of trial applications until the mid-2000s. With the introduction of high-performance smartphones, camera, graphics-processing capabilities, and inertial sensors, AR is getting more attention and prevailed (Ko, Chang, and Ji 2013).

Figure 1-2 Reality-virtuality continuum

Overall, mobile augmented reality has the following characteristics: 1) combines real and virtual imagery; 2) is interactive in real-time; 3) registers the virtual imagery with the real world; and 4) is accessed by mobile devices (Goh, Sunar, and Ismail 2019; Keating et al. 2011).

2.2 AR Tracking

The mechanism of AR is overlaying the augmented objected to reality through the mobile camera. To provide immersive AR experiences, the alignment of the augmented objects and their surroundings have to be reasonable. To do so, tracking is the crucial techniques that make the augmented objects show at a certain location. Tracking refers to the dynamic detection of spatial properties of the mobile devices or the targets of augmented objects. Another technique relates to tracking is registration. Registration accounts for the correct overlay display of virtual objects according to the tracking targets(Schmalstieg and Höllerer 2016). There are various kinds of tracking methods, and the common methods can be categorized into: 1) camera-based (marker-based and marker-less-based); 2) sensor-based (through inertial sensors); 3) location-based; 4) SLAM; and 5) hybrid tracking (Bekele et al. 2018; Kolivand et al. 2019).

Camera-based tracking depends on camera recognition techniques through the image processing algorithm of computer vision. Within camera-based tracking, marker-based tracking relies on recognizing the features of 2D targets. The 2D targets are usually matrix barcodes, and the images with distinct features also work. Once the markers are recognized, the virtual objects appear. It is the most affordable method because making the markers and anchoring the objects are relatively not difficult. Marker-less-based tracking is another tracking method of camera-based tracking. It also detects the targets by the camera, but it recognizes geometric features instead of 2D markers. The features are mainly based on the embedded 3D point cloud data.

Sensor-based tracking applies mobile inertial sensors like gyroscopes and accelerometers to detect the position of the mobile device and the augmented objects. Gyroscopes are used for detecting the angular velocity and orientation of the device. Accelerometers detect the gravitational acceleration for measuring the subtle movement of the device. They work together to track the pose of the mobile camera. Location-based tracking uses GPS to retrieve the relevant information according to the mobile location (Kolivand *et al.*, 2019). The use of a mobile camera is not necessary for location-based tracking, but it needs wireless networks to update the current information (Goh, Sunar, and Ismail 2019). One of the popular AR application that uses location-based tracking is Pokemon GO.

SLAM (simultaneous localization and mapping) is a relatively new technique which mainly applied in the field of robotic engineering. It allows the device to operate under an unknown environment and sense the surroundings for understanding the environment at the same time (Miyake *et al.*, 2017). It can also be applied to AR with camera detection. Visual SLAM can detect the distance and the features of the surface and provide instant tracking. For example, the application that detects the surface of the room for users to place the furniture. As for hybrid tracking, the combination of GPS and camera-based tracking is usually used (Bekele *et al.*, 2018). For good AR experience, accurate and robust tracking are necessary.

2.3 AR Interaction

Mobile interaction is the manipulation of the augmented 2D or 3D objects through mobile devices. The difference between AR and non-AR interaction lies in the integration of the background of reality. With real scenes as the mobile background, the stereoscopic sense of depth and distance is stronger. It also provides opportunities for users to communicate with reality. Mobile interaction consists of form-factor, human interaction and context-of-use challenges and has given rise to the study of mobile human-computer interaction (HCI) or mobile interaction design. The study of mobile interaction began since late 1990 and has become the major interaction medium for AR (Sá and Churchill 2013). The specialty of mobile interaction is that it requires users to operate on-screen hands gestures. There are also the limitations with screen sizes and the battery of the device which could lead to issues like fat-finger error, user fatigue and limited activity time. While most of the earlier AR systems were used to view augmented objects, there were no much supports creating or modifying the objects (Goh, Sunar, and Ismail 2019). Goh, Sunar, and Ismail indicated that AR interaction which involves object manipulation is one of the essential parts of AR. Their research focused on mobile AR manipulation and provided an overview of the techniques.

The manipulation techniques of mobile AR can be categorized into: 1) touch-based; 2) mid-air gestures-based; 3) device-based interaction. Touch-based interaction applies on-screen touch inputs for manipulating the 3D objects. It is one of the popular AR interaction methods due to the suitable implementation with mobile devices. Mid-air gesture-based interaction requires the detection of finger gestures as the inputs for controlling the 3D objects. As for device-based interaction, the manipulation relies on the mobile device itself, the 3D objects change when the users move the devices (Goh, Sunar, and Ismail 2019). The term "tangible interface" means to manipulate the augmented objects directly through real and physical objects. It usually detects the changes of additional objects or markers to adjust the AR display. The research field of the tangible user interface (TUI) also derived. The concept of TUI may be confused with graphical user interface (GUI), but GUI only works on the digital world without the involvement of real objects. However, mobile AR with touch-based interaction can also be regarded as a tangible AR because of the relation between the on-screen gesture and the augmented objects. (Bekele *et al.*, 2018).

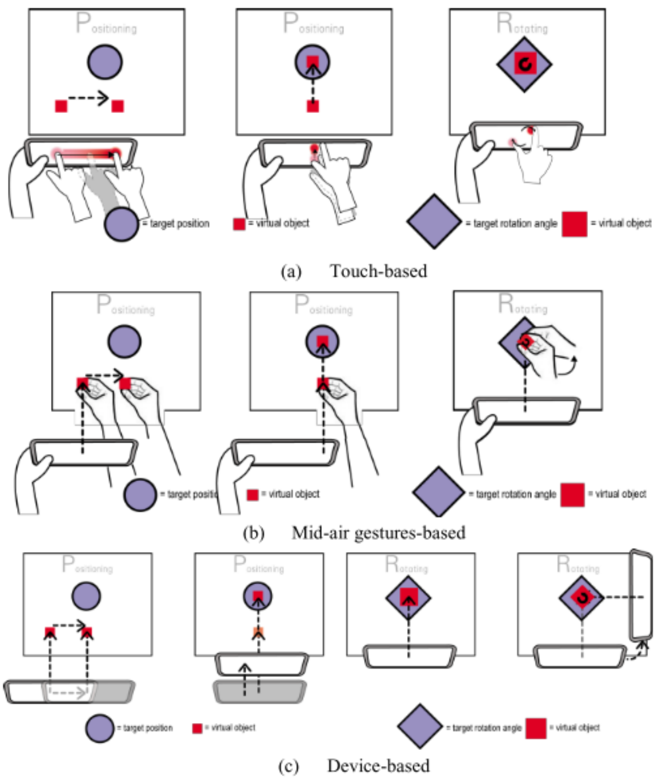


Figure 2-1 The concepts of mobile AR interaction techniques (Goh, Sunar, and Ismail 2019)

2.4 AR Visualization

The visualization of mobile AR is more complicated than the visualization with non-AR mobile applications because of the integration of the virtual and real world. The world of AR apps consists of 3 layers. The first one is the real world, which exists as the background in AR and is consistently captured by the mobile camera. The second is the augmented 3D world, where the virtual 3D objects appear and superimpose to the real world. The third is the screen space, where the 2D app interface displays and on-screen touches happen for touch-based interaction (Keil *et al.*, 2018). The visualization of augmented objects is the focus and plays an important role during immersive AR experience. For the visualization techniques of augmented objected, there are some common techniques as below (Schmalstieg and Höllerer 2016):

- Annotations and labels
- Highlights
- Assisting visual aids: helpers and guiding-geometry
- Additive elements: XRAY / Ghosting / Transparency
- Additive elements: explosion diagrams
- Trans-media material

Annotations and labels are the augmented objects that anchor to the reality for providing additional information. They can be icon-like labels or labels with leader lines. Some basic rules about the design of label placement in AR have been established (Grasse *et al.*, 2012). Highlights show different appearance to emphasize on the certain parts of the objects to draw users' attention. It can also be used as the interaction during selection indication. Assisting visual aids provide additional guidance for certain cases. A virtual guide for instructing the operation of a complex machine can be one of the examples. X-Ray or ghosting effect work with transparency to reveal the additional information which overlaps with the objects, for instance, to show the pipelines under the streets or to display the reconstruction of the ruins. Explosion diagrams show the expanded information in relation to the object. It presents the relationship between a series of separate images or objects, especially for the objects with a complex structure like machine and architectures. Trans-media material superimposes multimedia from 2D, 3D objects to video to the real world. In addition, Kjellmo suggested that sometimes the cartoony style of the 3D models makes the scene more believable in comparison to photorealistic style. It is because users have higher expectation and perception toward photorealistic objects since they already understand the notion of reality (Kjellmo, 2014).

2.5 3D Reconstruction

To restore the ruins of the archaeological sites, appropriate 3D reconstruction models are necessary. For building the 3D objects, there are 8 general requirements: 1) high geometric accuracy; 2) the capture of all details; 3) photorealism; 4) high automation level; 5) low cost; 6) portability; 7) application flexibility; and 8) model size efficiency. The importance of each of them depends on the purpose of the object (El-Hakim *et al.*, 2004). The methods of 3D reconstruction can be categorized as geometry-based Image-based modeling, range-based modeling, and image-based rendering (IBR). For the heritage sites without much remains, geometry-based modeling is used. It builds the models on scratch and applies material and texture by modeling software according to historical documents and other related research. This method is more time-consuming and less precise. The other two kinds of methods rely on advanced tools and technology. They are automatic and can create more accurate and realistic 3D models. Image-based modeling applies photogrammetry to capture 3D data from a set of 2D images by the mathematical model. It can create accurate data like the shading, texture, and contour of the objects. Range-based modeling uses active sensors like laser-scanners to acquire the dense 3D points of the geometry. IBR uses images that are based on automatic stereo matching from different camera positions to generate a new view for rendering without geometric representation (Kolivand et al. 2019; El-Hakim et al. 2004).

3 Methodology

This chapter describes the approaches and workflow of the research. As stated in the introduction, the goal of the research is to develop suitable guidelines for AR reconstruction. To explore the related factors, associated AR design elements are reviewed, which include the features of AR for reconstruction purpose, general AR design principles, the related research, and existing applications. After summarizing and analyzing each of them, a set of guidelines is proposed. Next, the guidelines are implemented into a case study and the evaluation is conducted to examine the outcome and effectiveness of the guidelines.

3.1 Features of AR Reconstruction

It is crucial to identify the features of AR reconstruction to understand the specific requirements before making the guidelines. Some of the features are derived from mobile AR techniques, and some are especially for the purpose of cultural exhibition. The 5 features are location-specific, rely on tracking and registration, tangible interaction, multimedia materials, reconstruction and exhibition purpose. The limitations of AR reconstructions are also discussed.

A. Location-specific

According to the location of the usage, the AR applications can be categorized into two types: outdoor or indoor, on-site or off-site applications. Due to the different environment, the purpose and requirements also vary. Indoor applications are usually used in museums for additional exhibition as “virtual museums”. The visitors can thus get closer to the augmented fragile objects and even interact with them (Kolivand *et al.*, 2019). In other hands, outdoor AR reconstruction often applies to larger objects like buildings and archaeological sites to make them appear like they were in the past. For off-site AR applications, the display of augmented objects is not specific to the location. For example, the simulation of Earth and the placement of the furniture. The AR effects can be shown once they are triggered. On-site AR effects require the users to position themselves at a certain location. Only when they are at the location, they can experience the AR effect which fit the surrounding environments. The tracking technique is crucial for this kind of AR. Once the users change the location or miss the targets, the augmented effects change as well. AR navigation and other location-based AR service can be the example of on-site AR. Besides, outdoor AR is also more challenging for making the shadows and lighting effect that cope with the environment (Bekele *et al.*, 2018).

B. Rely on tracking and registration

Since AR immerse experience requires good user perception toward the combination of augmented objects and the real world, the tracking and registration techniques are essential for the objects to appear simultaneously and seamlessly in reality. Marker-based tracking is usually used in an indoor environment because it is taken place in a relatively narrow space. With the space limitation, marker-based tracking can ensure the convenient synthesis of the virtual objects (Han *et al.*, 2013). However, the misuse of the markers could lead to the possibility of damage. For example, the fragile artifacts can't afford direct attachment of the additional marker. Outdoor AR relies heavily on marker-less and hybrid tracking because it is not suitable to track on a certain marker in wide-open areas. As stated before, marker-less based tracking depends on recognizing the object features. If the sites lack suitable features, the features may not be detected, or virtual objects could be miss-registered (Bekele *et al.*, 2018). As for location-based tracking with GPS, it may not be precise to be positioned in the urban environment with high-rise buildings and cause the failure of AR experience (Miyake *et al.*, 2017). Although sensor-based tracking is good at detecting subtle movements, it can only be an extension to other tracking devices as it is unsuitable to track the objects in a large area (Wolfenstetter, 2019). The survey of outdoor mobile AR applications for cultural heritages from Bekele et al. showed that 35% of the applications used marker-less-based tracking, 24% of them used sensor-based tracking and 41% of them used hybrid tracking. Each of the tracking methods has their advantages and disadvantages, the usage should depend on the conditions like requirements, environments and devices.

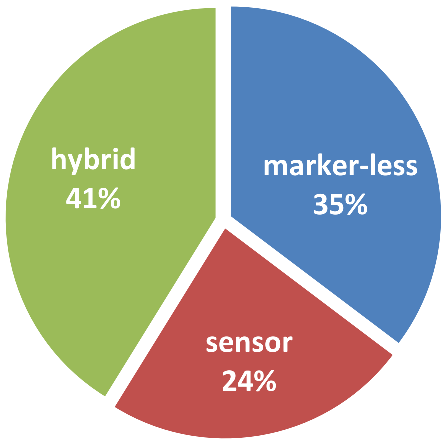


Figure 3-1 Outdoor MAR method for cultural heritage (2001-2016)
(Bekele *et al.*, 2018)

C. Tangible interaction

For mobile devices, tangible interaction is the main interaction methods. As stated in the last chapter, there are three kinds of mobile interaction methods which are touch-based, mid-air gesture-based and device-based. The interaction would require an intuitive human-computer interface and portable technology. For outdoor AR, most of them use tangible interface (Carmigniani *et al.*, 2011) which requires on-screen gestures like tap, press, and scroll to interact with the augmented objects. For AR interaction for cultural heritage contexts, the users should be able to interact with digital content naturally to get the information of the objects, and it should also enable the comparison and identification of artifacts (Angelopoulou, Economou, and Bouki 2012).

D. Multimedia materials

Some existing AR reconstruction applications use 3D models, historical images, or videos to show the scenes of the reconstruction. The usages of multimedia materials can virtually enrich the real world. Other than the reconstructed objects, multimedia can also be used as the explanation and information to make the AR application more diverse. The additional visualization and interaction like the methods of annotations, labels, highlight, and transparency can also be integrated together to the AR view (Keil *et al.*, 2018).

E. Reconstruction and exhibition purpose

The value of digitalized heritage is to provide additional and/or more in-depth information. Other than the preservation purpose, digital heritage provides opportunities for the professionals like historians, curators, and architects to evaluate and study the artifacts in different ways. It also enables visitors to have novel experiences to appreciate artifacts and history. The important thing is that digital tools should enhance rather than replace the cultural value (King, Stark, and Cooke 2016).

Some of the heritage sites were discovered accidentally and didn't get much public attention. In addition, the ruins themselves are not outstanding and attractive from the appearance, so they are easily overlooked. For the old buildings which have been torn down and rebuilt as modern architectures, it is hard for people to notice their past. From the perspectives of cultural preservation, it is better to keep the current appearance without additional changes. According to the Venice Charter, a set of guidelines for conservation and restoration of monuments and sites, the restoration must follow the historical truth and base on the respect for original material and authentic documents. Adolphe Napoléon Didron, a historian and archaeologists in 19th, once said: "for ancient monuments, it is better to consolidate than repair, better to repair than to restore, better to restore than to reconstruct". The restoration should stop when there is uncertainty because it would cause the falsification of history.

For some ancient but not famous architecture, there are no much related historical documents for people to trace back to. In this case, augmented reality is an appropriate tool to reconstruct digitally and won't cause adverse impacts on the cultural heritage site physically. A primary goal of digital cultural heritage is to show the relationship between the heritages and their surroundings and facilitate a broad public awareness as well as the appreciation of cultural heritage sites. With the interpretation of the technology, the significance from the historical, political, spiritual, and artistic facades of cultural heritages can be explored (Brizard, Derde, and Silberman 2007). Compared to non-AR tools, AR can provide a more intuitive way to perceive and easily compare the overview of the reconstruction with the surroundings. It enables visitors to visualize and interact with the reconstructed model (Bekele *et al.*, 2018).

F. Limitations

As stated in the background, the researches about AR design is just getting popular these years. Bekele et al. indicated that many AR applications of cultural heritage use interfaces in a much narrower scope than its potential (Bekele et al., 2018). Most of the interaction methods are still confined to mobile devices and can only be operated with one hand. For the content itself, the presentation of the AR with cultural heritages is often not in an interesting and appealing way (Cisternino, Gatto and De Paolis, 2018). Cultural heritage may not be a popular subject to the public, but the integration of attractive technology can help to raise public awareness of the significance of heritage. Thus, the value of cultural heritage can be conveyed more widely.

3.2 Existing AR Design Principles, Researches, and Applications

3.2.1 AR Design Principles

Some mobile AR design principles have been studied since the researchers noticed the lack of AR design research. The study of Andreas et al. was one of the first research to apply HCI principles to AR applications. It combined some user-centered design principles with the demands of AR and developed 9 principles for AR interface design. They are affordance, reducing cognitive overhead, low physics effort, learnability, user satisfaction, flexibility in use, responsiveness, and feedback, and error tolerance (Andreas *et al.*, 2007). More research about AR design principles was studied and followed by this research. The principles or guidelines were introduced from various kinds of aspects like usability, heuristics design, interface, and interaction. Many of them mentioned heuristic, which can also be referred to as design heuristics or heuristic evaluation. It means the guidelines that be used to evaluate the usability of a system and guide its design. It is also synonymous with guidelines in the field of interface design (Endsley *et al.*, 2017).

Ko, Chang and Ji. developed AR usability principles and conducted a heuristic evaluation to identify usability problems. First, they discussed 61 usability principles and classified the 22 final principles into 5 categories which are user-information, user-recognition, user-support, user-interaction, and user-usage. They validated the principles through user tests. The problems they found were duplicated expression of information, providing limited information, unfamiliar icon expression, expanding the range of search, help menu, and one-handed operation. And they proposed some guidelines to improve the problems (Ko, Chang and Ji 2013).

Table 3-1 Usability principles from Ko, Chang and Ji.

Principles	**Sub-principles**
user-information	defaults, enjoyment, familiarity, hierarchy, multi-modality, visibility
user-cognitive	consistency, learnability, predictability, recognition
user-support	error management, help and documentation personalization, user control
user-interaction	direct manipulation, feedback, low physical effort, responsiveness
user-usage	availability, context-based, exiting, navigation

(Ko, Chang, and Ji 2013)

From the aspect of interface design, the research of Santos, Miranda, and Araujo identified the issues of graphical user interface design of mobile AR. The highlighted issues are: appropriate usage of devices' sensors, low accuracy of tracking technologies, a range of hardware and software features and limitations, user interface design variability, lack of standards adopted by application developers RAM, energy consumption. They then make an AR prototype to evaluate the usability problems with user tasks. At last, they proposed specific guidelines for each of the GUI issues (Santos, Miranda, and Araujo 2017).

Table 3-2 GUI issues and guidelines from Santos, Miranda, and Araujo

GUI issues	Proposed guidelines
1. Not understand the application on first use. Provide	Provide a tour guide on the first use, stating the purpose of the application and how to use widgets.
2. Slide to control interest distance is not understandable.	Use known interactions on mobile touchscreen devices.
3. Map and AR browser without any POIs or direction indicators.	The application cannot run out of POIs, even if there is not any in the area. The direction of POIs can be suggested with arrows in the corner.
4. The textual distance information may go unnoticed by uses.	The application should provide visual feedback for distance information. For example, draw the POI as if they were on the horizon.
5. Update text labels to inform the selection of POIs.	The application should draw the user's attention. One suggestion is to shrink the exploration space to present the details of the POI.
6. Use popups to sho detail of POIs.	Popups can be difficult to close and overlaps navigation. The details of POIs should be presented in a space apart.
7. Scanner or Discover POIs automatically without proper notify the user or suggest what he could do next.	When a scanner or automatic selection occurs, the system must notify the user and suggest what to do next.

(Santos, Miranda, and Araujo 2017)

From the perspective of mobile AR interaction, the research of Kourouthanassis, Boletsis, and Lekakos developed 5 design principles based on the mobile AR interaction challenges. They also applied the proposed principles to examine the interaction of existing applications. They found that the feedback mechanisms of content privacy and infrastructure's status are usually ignored. Since most of the AR applications only involve independent users, the privacy issue should be considered for applications with social interaction. The principles and the interaction challenges are listed as below (Kourouthanassis, Boletsis, and Lekakos 2013).

Table 3-3 Design principles and challenges of AR interaction from Kourouthanassis, Boletsis, and Lekakos

Principles	MAR challenges
1. Use the context of providing content Employ sensor and marker technologies to collect contextual information	1) Minimize cognitive and information overload. 2) Expand the search range of desired information regarding an object in focus.
2. Deliver relevant-to-the-task content Filter (or personalize) interactive content based on multiple contextual criteria.	3) Expand the search range of desired information regarding an object in focus. 4) Enhance overall usability due to one-handed operation fo the application and difficulties to interact with small-sized icons.
3. Inform about content privacy Design the functionality around different privacy spheres.	5) Minimize the emergence of negative user emotions.
4. Provide feedback about the infrastructure's behavior The application should inform users regarding its current state or regarding changes in its state.	6) Enhance the learning curve of using the system. 7) Minimize user frustration from system slow or unexpected responses during user interactions.
5. Support procedural and semantic memory Employ familiar icons and/or interaction metaphors to communicate the application intended functionality and ensure soothe user interactions.	8) Enhance the learning curve of using the system. 9) Increase familiarity with the system. 10) Minimize the emergence of negative user emotions.

(Kourouthanassis, Boletsis, and Lekakos 2013)

The study from Ejaz *et al.* identified 10 AR interface design principles from previous research to explore the AR interface which can match the user efforts and the computer display. They also carried out questionnaires with the AR game Pokemon GO to validate the importance of the principles. The results showed that the principles are important for developing any AR system or interface (Ejaz *et al.*, 2019).

Table 3-4 AR GUI issues from Ejaz et al.

GUI design principles	Description
1. Affordance (Perceived affordance)	The relationship between the user interface and the underlying properties associated with it.
2. Visibility and natural mapping	The connection of what you need to do and what is seen conceivable. Great mappings use physical analogies or social models and can be easily recollected.
3. Low physical effort	Users should be able to achieve the task easily and comfortably.
4. Learnability	Learnability is related to how the user uses the system whether it can be easily used by simply recognizing the system or whether the user should recall everything by memorizing it.
5. User satisfaction	User satisfaction is related to the perceived user experience and
6. Feedback	Feedback can let users know the status of the system or what the user have to do next. It is especially important during the process of waiting and tracking.
7. Error tolerance	Developers should know the possible errors and help the users to overcome them.
8. Reducing the cognitive burden	Keep the user focus on the real task rather than making them mastering the interface. The cognitive burden could also decrease the learning effects.
9. Flexibility	Different modalities should be integrated considering varied user preferences and abilities.
10. Simplicity	Make the interface as efficient as possible.

(Ejaz *et al.*, 2019)

The study from Endsley *et al.* summarized the existing heuristics in AR space, including video game heuristics and AR interaction. The 97 heuristics were evaluated by experts and be leveraged through iterations of affinity diagramming process. The final 9 AR heuristics are listed as below (Endsley *et al.*, 2017).

1) Fit with user environment and task.
2) Form communicates function.
3) Minimize distraction and overload.
4) Adaptation to user position and motion.
5) Alignment of physical and virtual worlds.
6) Fit with user's physical abilities.
7) Fit with user's perceptual abilities.

8) Accessibility of off-screen objects.
9) Accounting for hardware capabilities.

The research from Gómez, Caballero and Sevillano created a checklist for heuristic evaluation on the mobile interface. First, they defined the problems and constraints on mobile, which includes 1) limited input/output facilities; 2) mobility and varying context; 3) different type of tasks; 4) multidevice access; 5) limited processing capability and poser; and 6) adoption. Then, they developed 13 principles from the defined problems. The principles are listed as below (Gómez, Caballero, and Sevillano 2014):

Table 3-5 Mobile heuristics and sub-heuristics from Gómez, Caballero and Sevillano

Mobile heuristics	Sub-heuristics
1. Visibility of system status	1) System status feedback 2) Location information 3) Response time 4) Selection / input of data 5) Presentation adaption
2. Match between system and the real world (mental model accuracy)	1) Metaphors / mental models 2) Navigational structure 3) Menus 4) Simplicity 5) The output of numeric information
3. User control	1) Explorable interface 2) Some level of personalization 3) Process confirmation 4) Undo / cancelation 5) Menu control
4. Consistency	1) Design consistency 2) Naming convention consistency 3) Menus / task consisteny 4) Functional goals consistency 5) System response consistency 6) Orientation
5. Error prevention	1) Fat-finger syndrome
6. Recognition rather than recall	1) Memory load reduction 2) General visual cures 3) Input / output data 4) Menus 5) Navigation
7. Flexibility and efficiency of use	1) Search 2) Navigation
8. Aesthetic and minimalist design	1) Multimedia content 2) Icons 3) Menus 4) Orientation 5) Navigation

Mobile heuristics	Sub-heuristics
9. Help users recognize, diagnose and recover from errors	
10. Help and documentation	
11. Skills	
12. Pleasurable and respectful interaction	1) Input data 2) Shopping 3) banking
13. Privacy	

(Gómez, Caballero, and Sevillano 2014)

The summarized 49 design principles are classified and listed as Table 3-6. Some common and repeated principles are found. For example, the consideration of cognitive load, physical efforts, user supports, feedback, and intuitive interaction. These are all important to mobile AR interaction and interface design. Since AR users have to deal with the virtual and real world together in the devices with limited space, it could easily cause visually overwhelmed. The use of familiar metaphors for the icons, interaction or other design elements and the efficient interface can contribute to preventing cognition overload. Considering the operation of AR applications, it takes time for users to get used to and the function is different between each application. As for the usage of AR, since the function and operation are different between each AR application, providing user guide and feedback can efficiently guide the users and prevent user frustration. The applications of AR reconstruction don't usually require personal. They should inform the users whether they consent the access or preservation of personal data like location and album.

Table 3-6 The summarization of AR design principles

Sources	**(Ko, Chang, and Ji 2013)**	**(Endsley *et al.*, 2017)**	**(Gómez, Caballero and Sevillano, 2014)**	**(Santos, Miranda, and Araujo 2017)**	**(Ejaz *et al.*, 2019)**	**(Kourouthanassis, Boletsis, and Lekakos 2013)**
Purpose	**Usability principles for MAR**	**AR design heuristics**	**MAR heuristic evaluation**	**GUI for MAR**	**GUI for AR**	**MAR interaction design principle**
Princi-ples	• **user-information** defaults, enjoyment, familiarity, hierarchy, multi-modality, visibility	• Minimize distraction and overload • Alignment of the physical and virtual world	• Aesthetic and minimalist design • Match between the system and the real world	• The application should draw the user's attention • The details of POIs should be presented in a space apart.	• Visibility and natural mapping • Affordance or perceived affordance • Simplicity	• Deliver relevant-to-the-task content
	• **user-cognitive** consistency, learnability, predictability, recognition	• Form communicates function • Fit with user's perceptual abilities	• Consistency		• Learnability • Reducing the cognitive burden	
	• **user-support** error management, help and documentation personalization, user control		• Error prevention • Help user recognize and recover from errors • User control: straight gesture, and permanent main menu • Help and documentation	• Provide a tour guide on first use, stating the purpose of the application and how to use widgets • When a scanner or automatic selection occurs, the system must notify the user and suggest what to do next.	• Error tolerance	
	• **user-interaction** direct manipulation, feedback, low physical effort, responsiveness	• Adaptation to user position and motion • Fit with user's physical abilities • Accessibility of offscreen objects	• Visibility of the status • Skill: intuitive operation	• The application should provide visual feedback for distance information. • Use known interactions on mobile touchscreen devices. • The direction of POIs can be suggested with arrows in the corner.	• Feedback • Low physical effort	• Provide feedback about the infrastructure's behavior • Support procedural and semantic memory
	• **user-usage** availability, context-based, exiting, navigation	• Fit with user environment and task	• Flexibility and efficiency of use • Recognition rather than recall		• Flexibility	• Use the context for providing content
			• Pleasurable and respectful interaction		• User satisfaction	
			• Privacy			• Inform about content privacy
		• Accounting for hardware capabilities				

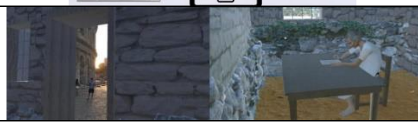
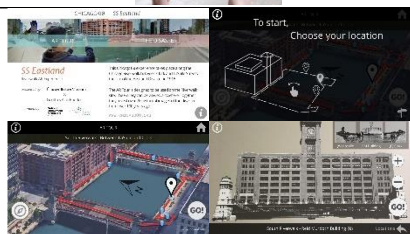
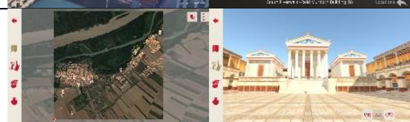
3.2.2 The Research and Existing Applications

This section discusses the mobile AR research and existing mobile AR applications for reconstruction purpose. For the AR applications, only the interface and design of the AR applications are investigated, the actual AR effects of the existing applications are not included in this research due to the location limitations. Most of them use 3D models to show reconstruction. Some applications apply 2D historical photos to superimpose to specific scenes. Some 3D models are reconstructed as whole buildings. Some models only rebuild the missing parts and keep the existing structure. Cannella developed this kind of AR reconstruction for both outdoor and indoor environment. In an indoor museum, the reconstruction of an old temple was displayed and matched to the ruins of the temple to show their relation. The effect makes it clear to see which parts are reconstructed (Cannella, 2019).

The appearance of 3D models can be applied to texture, light and shadowing effect to make them more realistic. The research of Boboc et al. made the entire model of a Rome house including the interior space. There was also an animation that showed Ovid, an ancient Roman poet, writing on his desk. When the users go inside the building, they can see the animation and even hear a voice reading Ovid's poem (Boboc *et al.*, 2019). It utilized different types of multimedia together in the AR experience. As for special AR effects, the ghosting effect is commonly used for the reconstruction objects. Some of the applications provide a slider bar for the users to adjust the transparency of the virtual objects. The function makes it more obvious to compare the difference before and after the reconstruction. Some applications use animation as a reminder to tell the users where to find the targets.

Many of the applications provide maps to show the location and distribution of the points of interest. They can be in different kinds of forms, like web-map (Lee et al. 2012; Aoyakamijichi AR) or the maps based on computer graphics (Cavallo, Rhodes, and Forbes 2017; Caistor AR). Some of them display the current user location. Different map layers like historical maps and aerial images that show the current land surface can enable users to compare the landscape changes in a different era (Carnuntum APP). The signals for the suggested route of visiting can also be added to guide the visitors. For showing objects in different time periods, a slider bar of the timeline can be applied for the users to choose (Cisternino, Gatto, and De Paolis 2018; Krogstie and Anne-Cecilie Haugstvedt 2012). To provide user guides, some applications show the guides right after launching the applications to teach the users in the beginning. Some provide the guides as an icon which allows the users to reach when they have questions.

Table 3-7 The design of existing applications for AR reconstruction

Sources	Type	Design	Images
(Cannella, 2019)	AR research	It shows the missing part of the building. It also provides a slider bar to adjust the transparency.	
(Pettitt and Fuhrmann 2017)	AR research	3D reconstruction of the Robinson house in Manassas National Battlefield Park.	
(Boboc *et al.*, 2019)	AR research	3D reconstruction of a Rome house with animation and voice	
(Cisternino, Gatto, and De Paolis 2018)	AR research	It presents the buildings in different time periods. It can detect the distance between the mobile and the target and provide detailed information dynamically.	
(Lee *et al.*, 2012)	AR research	It shows virtual 3D buildings which were affected by the earthquake. There is a map with the popups of POIs.	
(Kasapakis and Gavalas 2016)	AR research	It uses location-based AR with GPS. The tags of POIs are positioned at a specific location. The users can click the tags to see the explanation and images.	
(Rainio, Honkamaa, and Spilling 2015)	AR research	It uses location-based AR to superimpose historical photos to reality.	
(Krogstie and Anne-Cecilie Haugstvedt 2012)	AR research	It shows historical photos and provides a timeline for the users to choose the scene in different period.	
(Cavallo, Rhodes, and Forbes 2017), Chicago00 - The Eastland Disaster	AR research, an existing app	It uses marker-less based tracking to show historical photos when the camera is aligned with specific environmental features.	
Carnuntum APP	An existing app	It provides both AR and VR experience to view the reconstruction of the archaeological sites.	
Aoyakamijichi AR	An existing app	It provides animation for searching the targets. There is a handbook function for users to collect virtual artifacts.	
Caistor AR	An existing app	It provides both AR and VR for Caistor Roman town. A user guide shows after launching the app. There is a map with suggested visit route and tell the users what they can do at each location.	

3.3 Design Guidelines for AR Reconstruction

Through the summarization of technical requirements, features of AR reconstruction, the related research, and applications, the mobile AR design guidelines for reconstruction purpose are developed. The research from Cisternino, Gatto, and De Paolis pointed out some important consideration for AR reconstruction. The consideration are: 1) quality of 3D models, faithful to the historical truth and in line with the archaeological studies; 2) balance of virtual contents with additional text, audio, video; 3) identification of the most effective tracking method; 4) fast-tracking and overlapping of the 3D models over the image; 5) choice of an interaction modality for the user; and 6) pleasant and captivating graphic design (Cisternino, Gatto, and De Paolis 2018). Based on the consideration and the above findings, a set of 6 AR design guidelines for reconstruction purpose were proposed. The guidelines are:

1. Suitable tracking method – use suitable tracking to achieve high accuracy, responsiveness, and low latency
2. Quality 3D models – make the balance between user experience and hardware performance
3. AR interaction versus non-interaction – to explore or to present
4. Storytelling - design and present appealing stories to interest the public
5. Provide user guide and feedback
6. Prevent cognition overload

The relation between the guidelines and the findings of AR reconstruction is presented in table 3-8. Each of them is elaborated as below.

Table 3-8 The relation of the proposed design principles

Guidelines / Summarizations	Suitable tracking method	Quality 3D models	AR interaction versus non-interaction	Storytelling	Provide user guide and feedback	Prevent cognition overload
Technical requirements	×	×				
Features of AR reconstruction		×	×	×		
Research for AR reconstruction			×	×		
Developed AR application			×	×	×	
General AR design principles	×		×		×	×

× = the guideline is related to the summarization

A. Suitable tracking method – use suitable tracking to achieve high accuracy, responsiveness, and low latency

Tracking is the crucial technique to display augmented objects at a specific location. It must work with high accuracy, responsiveness, and low latency to achieve good AR experiences. Among the tracking methods, marker-less-based, sensor-based and hybrid tracking is the most common methods. Each of the tracking methods suits different environment. For example, marker-based tracking is not suitable in an outdoor environment as many studies have mentioned. The tracking methods are provided by software development kits (SDKs). Each SDK has distinct features and supports different kinds of tracking methods. Most of them work on both iOS and Android devices. As for the license of SDKs, some are free and some are free with limited functionality. The selection of the SDK should consider the environment of the project, requirements, budgets, etc. The table below lists the comparison of some common AR SDKs.

Table 3-9 A comparison of some common AR SDKs

SDK	Tracking methods			Platforms	License
	Camera	Sensor	SLAM		
Apple ARKit	2D, 3D object tracking	GPS, IMU	No	iOS	Free
Google ARCore	2D tracking	GPS, IMU	Yes	iOS, Android	Free
ARToolKit+	2D tracking	-	No	iOS, Android	General public license
Wikitude	2D, 3D object tracking	GPS, IMU	Yes	iOS, Android	Free and commercial
Vuforia	2D, 3D object tracking	GPS, IMU	Yes	iOS, Android	Free and commercial
Kudan	2D, 3D object tracking	GPS, IMU	Yes	iOS, Android	Free and commercial
MaxSt	2D, 3D object tracking	-	Yes	iOS, Android	Free and commercial
EasyAR basic	2D tracking	-	No	iOS, Android	Free
EasyAR Pro	2D, 3D object tracking	-	Yes	iOS, Android	commercial

Modified from (Bekele et al. 2018; Voinea et al. 2019)

B. Quality 3D models – make the balance between user experience and hardware performance

The reconstruction of 3D models is an essential part of AR displays. The main focus is to build the objects with correct scale and geometry based on the historical truth. With high-tech tools, the archaeological sites or the ruin can be modeled in geometrically accurate and photorealistic ways through photogrammetry or laser scanning. However, the reconstruction of the absent objects that can not be seen nowadays relies on historical documents and data. There are many methods for building 3D models. No matter which method is adopted, the goal is to achieve clear communication between the models and users. Besides, the size of the models could affect AR performance. The model with over-complicated geometrical complexity, shader and render could interrupt AR experiences. The details of 3D models should be balanced between user experience and hardware performance.

C. AR interaction versus non-interaction – to explore or to present

The representation of the augmented objects can be static or interactive. The static presentation allows the users to understand the information which is already displayed, and interactive presentation helps the users to explore the unknown parts. It can even increase their motivation to delve into the application. The similar demands of AR interaction can be compared to the demands for interactive cartography. Keil et al. developed the AR visualization cube which was based on the cartography cube from MacEachern. The cartography cube describes the level of human-map interaction versus to visualization communication. The task for revealing unknowns requires higher user interaction and brings about more private user usage and experience which is different individually. Therefore, the users can form insights through the interaction and create exploratory visualization communication (Roth, 2013). For the AR visualization cube, it explains the correlation of user interaction, informativeness, and adaptiveness to the effort of knowledge transfer. The higher level of efforts for knowledge transfer, which means visual thinking, requires higher interaction and informativeness. The AR display with low interaction is more suitable for static presentation and needs higher user adaptiveness for understanding the given information. The AR display with high interaction needs to be designed sophisticatedly for information extraction during the interaction process (Keil *et al.*, 2018).

For the interaction itself, transparent and highlight effects are the common ways to interact with the objects for archaeological sites. The additional text or images of the tags can be displayed at a fixed location to decrease interface complexity and prevent occluding other objects. When using AR apps, users hold the mobile device to focus on the object by one hand and perform onscreen touch by another hand(Goh, Sunar and Ismail, 2019). User fatigue might happen during long-time operation and complex interaction gestures which require more physical effort. The interaction should be performed with known, easy and intuitive gesture (Tsai, Chang, and Yu 2016; Santos, Miranda, and Araujo 2017).

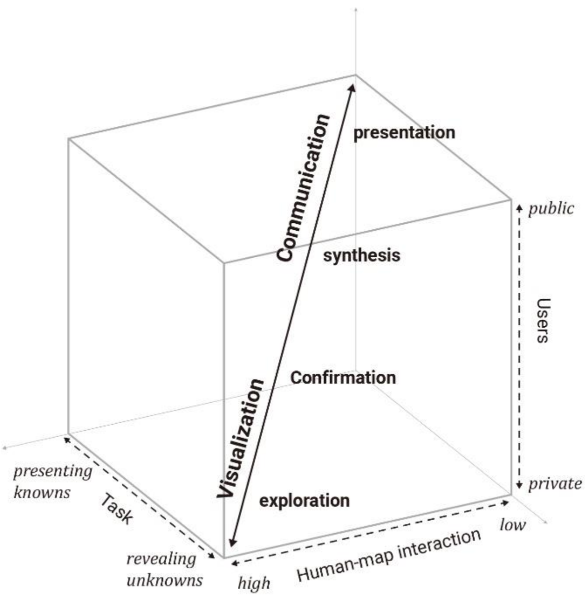


Figure 3-2 Cartography cube
Figure redrawn from (Roth, 2013)

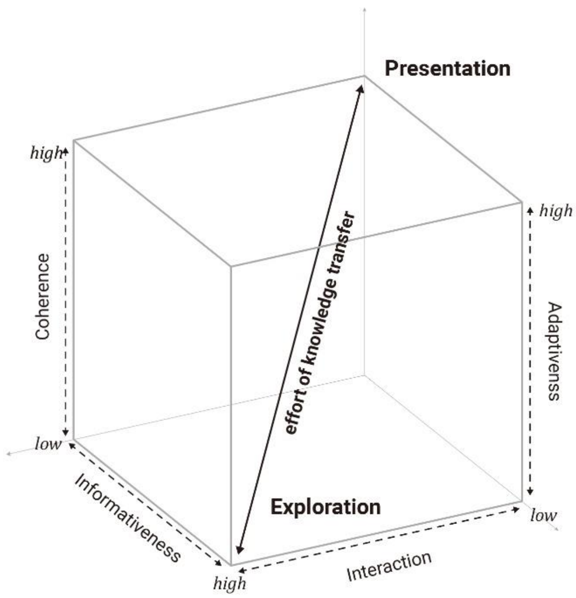


Figure 3-3 AR visualization cube
Figure redrawn from (Keil et al., 2018)

D. Storytelling – design and present appealing stories to interest the public

One of the purposes of virtual reconstruction is to facilitate broader public awareness and appreciation of cultural heritage sites(Brizard and Derde 2007). Apart from the beauty of objects which can be conveyed through 3D modeling, the stories behind them are also important to link the history and their current surroundings together. The ways to design and present the intriguing stories of the heritage sites is necessary to interest the general public.

Heritage sites often locate in large and spacious fields or even form heritage parks. In the context of the geographical feature, maps are suitable for presenting their location and spatial relation. General maps, aerial images, and historical maps can be applied to explain the geographical and historical relationship between the heritage sites and their surroundings.

E. Provide user guide and feedback

User guide and feedback are more specific to the interface issue that arises from the user side. Considering the complexity of the AR interface, this principle is especially helpful for AR design. Thus, this guideline is independent of other interface design principles. Apps without effective user guide or feedback could lead to user frustration. A user guide would be beneficial to the users who use the app for the first time. It can effectively guide the users to understand the function and what they can do with the app. Since AR is still a relatively new technology, it is especially important for the people without previous AR experience. Besides from user guides, feedback can also reduce user confusion and misuse by keeping the users informed about the current status of the system. Thus, the users won't be confused about their action and they can understand what to do next. It could be in the form of graphics or textual form (Andreas et al. 2007; Ejaz et al. 2019). For example, some visual or audial responses appear after clicking action, or off-screen indicator for showing where the augmented objects would appear.

F. Prevent cognition overload

The blending view of augmented objects with reality could easily cause visual overload, so more emphasis is put on user interaction, support and cognitive. Cognitive load means the mental effort used during operating the app. The cognition overload could lead to user distraction and lower down the user interest. To avoid cognition overload, the designed elements should build on familiar metaphor to reduce memory load. The overall design should be consistent to decrease user confusion. User cognition is also related to learnability which is about the easiness for learning and using the system (Tsai, Chang, and Yu 2016; Ko, Chang, and Ji 2013; Ejaz et al. 2019).

To the overall interface design, many AR design principles suggest that the design of the AR interface should not be complicated. Since the users need to cope with the mobile interface, the augmented objects, and the reality together at the same time, using a complex interface could cost more user attention and lead to unsatisfying user experience. The simple design of interface can minimize the visual distraction and allow the users to focus on the immersive interactive experience (Endsley et al. 2017; Tsai, Chang, and Yu 2016; Keil et al. 2018). The interface should provide some essential function, and the appropriate scale is between the interface complexity and user motivation (Roth, 2013).

For displaying POIs, they should be emphasized by personalizing or filtering to deliver relevant-to-the-task content. The detail of POIs should be presented in a space apart because popups can overlap other information and sometimes are difficult to close(Santos, Miranda, and Araujo 2017).

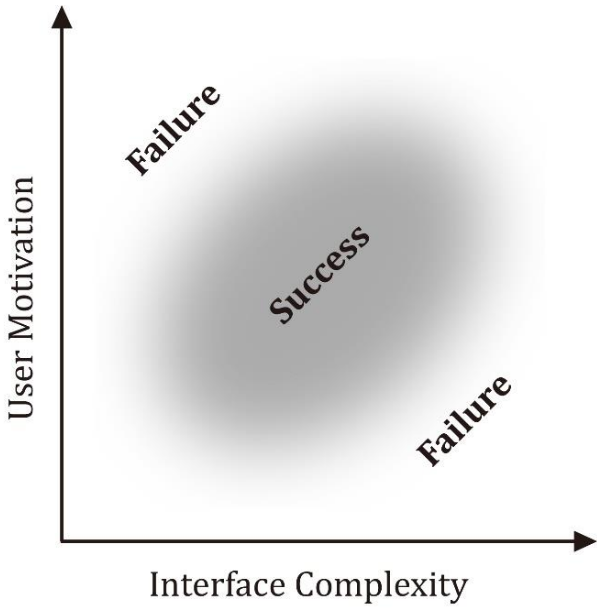


Figure 3-4 Interface complexity versus user motivation
Figure redrawn from (Roth, 2013)

4 Case Study

To examine the effectiveness of the proposed AR design guidelines, a case study was conducted with a practical AR application and an evaluation. A ruin of a medieval tower in Munich city center was chosen. The history of the site was also studied. This chapter describes the process of developing the prototype. After the development, user tests were conducted for the evaluation.

4.1 Prinzessturm

The ruin is called “Prinzessturm” or “Scheibling an der Herrenstrasse” which locates at Thomas-Wimmer-Ring 1 in Munich, Germany. Prinzessturm was first mentioned in 1473 as the name Scheiblingturm and it stood at the most eastern part of the city fortification. The name of Scheibling refers to its round shape. There was also another Scheibling at Frauenstrasse and called “Fischerturm”. Both Scheibling were round gun turrets that stood at the second city wall (in the front of Zwinger) for defending the city with guns and a moat (a ditch around a city).

Prinzessturm was built beside the tower “Lueg ins Land” which built in the 1330s and torn down in 1807. There was a nearly perpendicular turn of the city wall at Prinzessturm. The west part of the wall connected to Isartor and the other part went to the north direction. Prinzessturm was used as a prison around 1786 and became grain storage after that. It was called Prinzessturm since the 19th century but without any concrete historical reference. The demolition of the tower happened in 1892 for a new building. Around 1978 to 1988, the remains of Prinzessturm were uncovered due to the new construction. After the discovery, the ruins have been kept in the courtyard and open to the public (Landeshauptstadt München, 2019). The round base of Prinzessturm and parts of the wall that extended to west and north direction still remain. The brick structure and a door-like structure can be clearly observed from the ruins of the base. However, due to the high modern buildings around the ruin, pedestrians could hardly be aware of the ruins of Prinzessturm, and there is no information board for explaining the ruin. The ruin of Prinzessturm and parts of the wall of Jungfernturm at Jungfernturmstraße are the only remains of Munich fortification other than Isartor, Sendlinger Tur and Karlstor.

Figure 4-1 The drawing of Munich city fortress from Gustav Steinlein

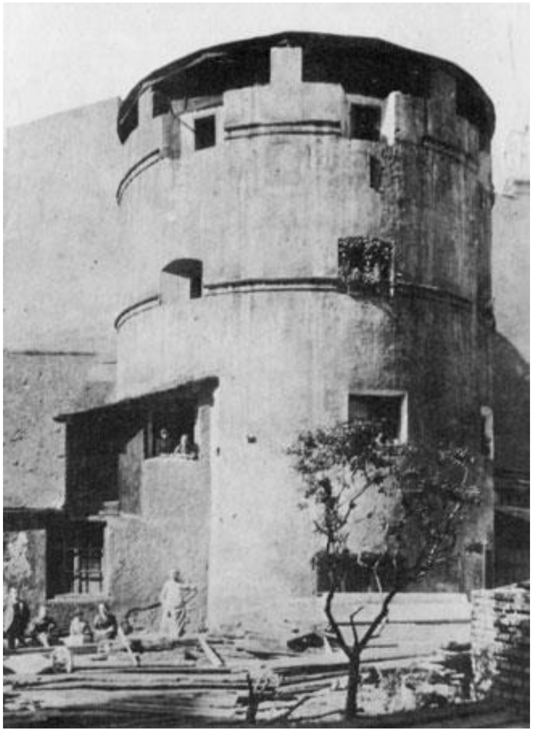


Figure 4-2 The historical photograph of Prinzessturm (in 1890)

Figure 4-3 The ruins of the base of Prinzessturm

Figure 4-4 The surroundings of the ruins (2019)

Figure 4-5 The view of the backyard

Figure 4-6 The view from Thomas-Wimmer-Ring

4.2 Project Set-Up

This section is about the development of the AR application. It starts from building a 3D model of Prinzessturm which was based on the historical images. Then the model was implemented in Unity with Wikitude SDK for the AR development. The reconstruction model of Prinzessturm can be displayed when the mobile camera detects the ruin. The design of the app was integrated with the proposed design guidelines and focused on AR interaction. The effects will be further evaluated in the next chapter.

4.2.1 3D Modeling

The 3D model of Prinzessturm was built with Blender 2.79, an open-source 3D computer graphics software. The scale of the tower was according to the historical image in 1890, which is the only accessible and reliable historical document so far. The roof and the body of the tower were set individually for later manipulation of the augmented object during app development. The base shape of the tower was made as a polygon instead of a circle to decrease the complexity of the geometry and speed up the performance of the model. The shape of the windows is almost square and the opening at the outside is a little bit larger. Under the windows, there are grooves around the tower.

Figure 4-7 The 3D model of Prinzessturm

4.2.2 Tracking

For developing the AR application, Wikitude SDK was applied. Wikitude provides include 2D image tracking, 3D object tracking, GPS and SLAM tracking. Considering the requirement of higher accuracy between the augmented object and the ruins of Prinzessturm, the 3D object (marker-less-based) tracking method was applied. GPS tracking might not be appropriate for Prinzessturm because the ruins are in the yard with a lower ground plane and surrounded by high buildings. The accuracy of GPS could be affected by the surround high-rise building and causes the tracking with low accuracy (Miyake *et al.*, 2017). The property of the height is also not easy to adjust with GPS. As a result, marker-less-based tracking would be a better AR tracking method in this case.

3D object tracking is through recognizing the traits of the object which are based on point cloud data. The point cloud data of the ruins was built with Wikitude Studio. It provides the tool to create the point cloud automatically by overlaying several photos from various angles of the site. Based on this method, the reconstruction model can appear immediately when the camera identifies the ruins. This tool was one of the most accessible and simple methods for this research to create the tracking target. Although the density of the point cloud data was not high enough, the result of the AR display was still satisfying. After reconstructing Prinzessturm, the model was exported to the file format which can cooperate with Unity.

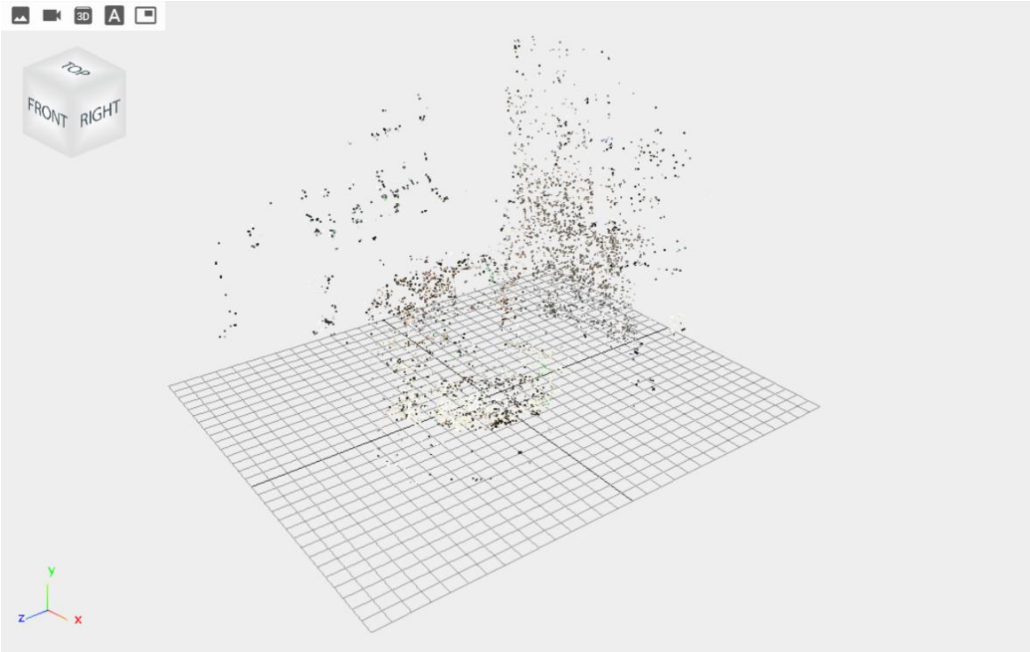


Figure 4-8 The point cloud data of the ruins

4.2.3 App Development

The development of the app was through Unity 2018.4.1f1 with Wikitude. Unity is a game engine software which can be cooperated with multiple AR SDKs for AR development. First, the 3D model, the point cloud data of the ruin and Wikitude SDK were imported to Unity. To match the point cloud data and the model, Wikitude camera was set for identifying the ruin and show the model. Then, the scale and the position of the 3D model were adjusted to make Prinzessturm appear correctly at the top of the ruin.

The design of this application was integrated with the proposed 6 design guidelines. The relation between the guidelines and the app design can be seen as Table 4-1. In addition, the ruin of Prinzessturm is beside the parking place where Chinese group tourists get on and off the tour buses. Sometimes there are tourists passing through or waiting around the ruins. Considering the possibility of Chinese respondents, the application provides two language options, English and simplified Chinese, for the users to choose. As for the mobile interface, there is a toolbar at the bottom of the screen. When the app is launched, there is a welcome page that states the purpose of the app and explains the function of the icon. After choosing the language, the screen changes to camera mode and a guiding image appears to tell the users to focus on the ruin. Once the mobile detects the ruin which corresponds to the point cloud data, the model of Prinzessturm appears. The 3 icons at the toolbar have different functions. The first one is the help icon which shows the guide of the app. The users can be informed of the basic information and an easy guide of the app. The second icon is for the page of more information. It shows the story of Prinzesssturm with some texts and the images of different time periods. The third icon is for the map page. It shows the location of each gate and tower of Munich city fortification in the past. It tells the relation of each construction, also, the gates that still exist like Isartor and Sendlinger Tur are pointed out. For the interaction with the 3D model, the users can click the information boxes in front of the tower, the roof and the wall to know the further explanation of each structure. When the information boxes are clicked, the color of the structure changes as the highlighted selection notification. A short period of the description also appears at the top-left corner of the screen.

Table 4-1 The relation of the guidelines and the app design

Proposed AR design guidelines	Prinzessturm App
1. Suitable tracking method	Marker-less-based tracking is applied considering the local environment of the tower. The detection of the base of the ruins can trigger the AR display.
2. Quality 3D models	The appearance and scale of the 3D model based on historical images.
3. AR interaction versus non-interaction	The highlight visualization appears when the users click on the information box beside the specific tower structure. After clicking, the color of the object changes and the corresponding texts show for more explanation.
4. Storytelling	Provide images with detailed information about Prinzessturm and a map to show the relation of the tower with Munich city fortification.
5. Provide user guide and feedback	The function of the app and the icons is stated in the welcome page. There is a guiding image tells the users where to focus on the mobile camera.
6. Prevent cognition overload	There is a toolbar with three icons at the bottom of the screen. The images of the icons are simple and related to the metaphors in reality.

Figure 4-9 The welcome page

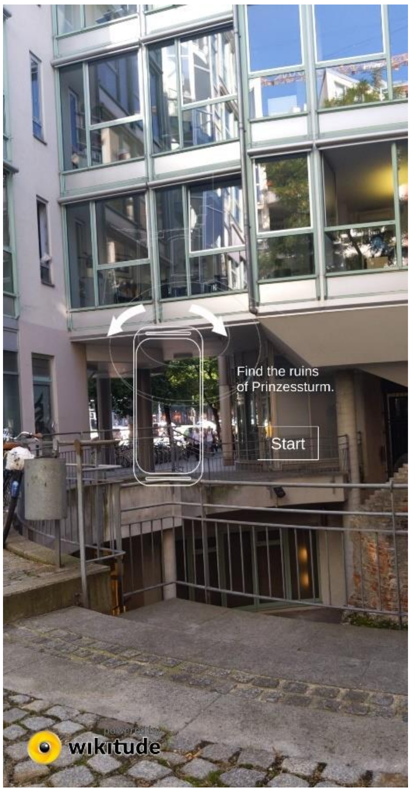


Figure 4-10 The guiding image (English)

Figure 4-11 The guiding image (Chinese)

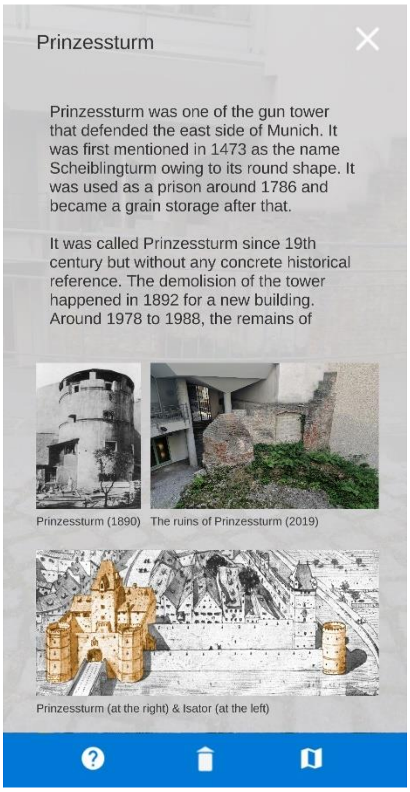


Figure 4-12 The information page (English)

Figure 4-13 The information page (Chinese)

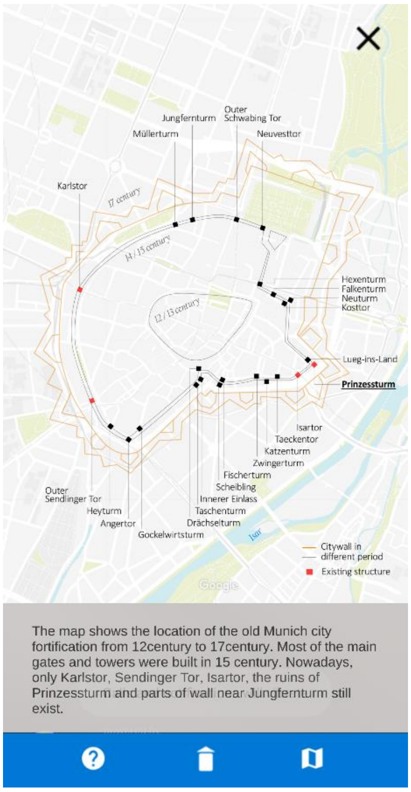


Figure 4-14 The map page (English)

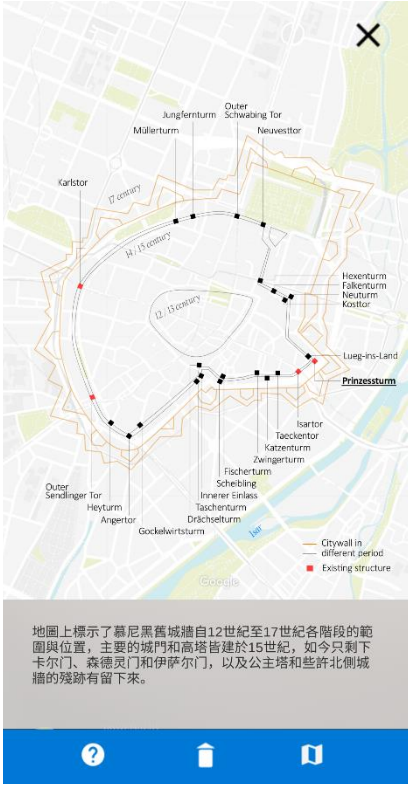


Figure 4-15 The map page (Chinese)

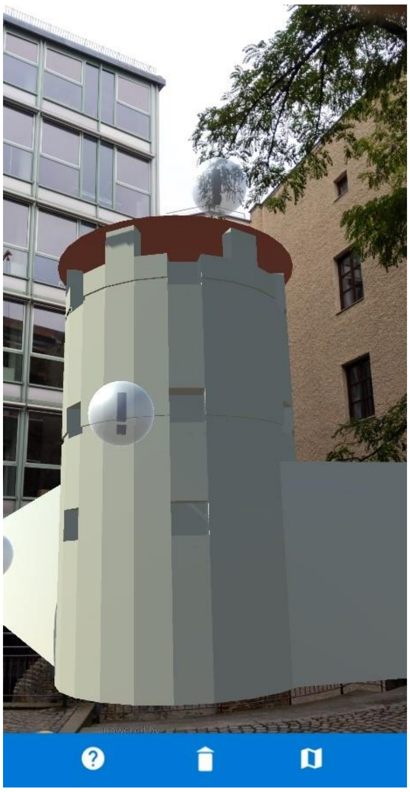


Figure 4-16 AR mode

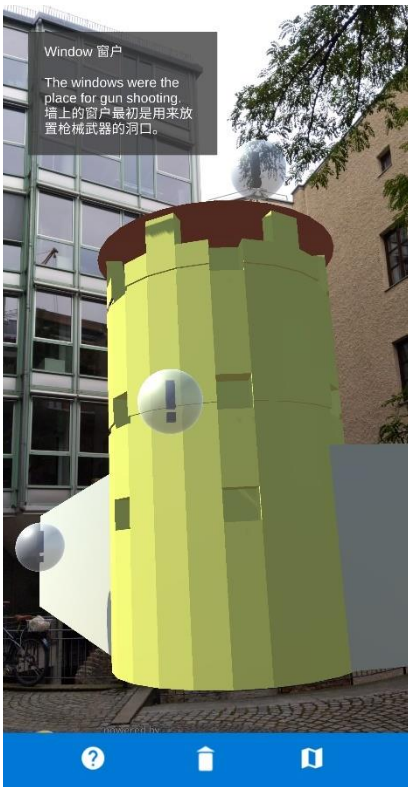


Figure 4-17 AR mode with highlighted the object

4.3 Constraints

In the case study, there are some constraints due to the used software and the current environment around the base of Prinzessturm. The main constraint is the occlusion problem. it is caused by the environment of the yard. The yard where the ruins of Prinzesturm locates is lower than the floor that the general public can access. If the model is positioned at the top of the ruins without empty space between them, the users would see the AR effect with the model crossing the floor. Thus, there was a space between the model and the ruin to improve the AR effect but it made the model look like floating on the floor. Another constraint is about AR tracking. When the camera moved too fast, the 3D model could shake or become tilt and decrease user satisfaction.

The app was planned to implemented with offscreen indicators. Some design principles indicated that offscreen indicator is a good function for guiding users where they can target the objects when the objects are offscreen. But in this case, offscreen indicators are not applicable. They require other reference objects to anchor the indicators.

5 Evaluation

This chapter describes the design, process, and results of the evaluation for the proposed guidelines. After developing the app that applied the proposed AR design guidelines, it is important to examine the user satisfaction and the effectiveness of the guidelines. The evaluation results can also respond to the research objectives and questions in the first chapter. The evaluation was conducted on-site at Prinzessturm with the developed mobile application.

5.1 Experiment Design

5.1.1 Evaluation Goals

The aim of the evaluation is to investigate the effectiveness of the proposed AR design guidelines for reconstruction purpose and both advantages and disadvantages of the app. The users will be asked about the overall satisfaction and suggestion after using the app. Within the 6 design guidelines, the effectiveness of the guideline “static versus interactive AR presentation” will be investigated specifically through the user surveys. Also, there will be interviews with the experts to see the thoughts from the professional side.

5.1.2 Material and Participants

The user tests were conducted at the ruin of Prinzessturm in Munich with the mobile device, Google Pixel 3 XL, which was provided by the Chair of Cartography of the Technical University of Munich. To investigate the effectiveness of AR interaction, the users were divided into two groups and used different applications. The used application was as stated in chapter 4.2. The only variable between the two groups was the interactive function in the application. The provided knowledge for two groups was the same, but there was the function for highlighting the color and showed additional texts in the first application when the users click on the objects. The interaction and the additional texts worked as the emphasis of the information. They can also be informed of the same knowledge of the tower from the information page. The second user group could only get informed about the tower from the information page. There was no interaction with the 3D model for them.

There were 26 participants participated in the evaluation. Among the participants, 14 users were in the first group and 12 users were in the second group. For the user type, there were 19 tourists, 3 local citizens, and 4 foreign workers or students. Many of them were Chinese tourists since the location is close to the parking place of tour buses for group tours. There were 15 male and 11 female and 53.85% of the participants were between age 21 to 40. There was 88.46% of the users who had previous AR experience. About the previous knowledge of Prinzessturm, no one knew the story of the ruins. The detailed statistics of the participants are as Table 5-1.

Table 5-1 The basic statistics of the participants

Type		**Group1**	**Group2**	**Total**	**Percentage**
Age	Below 20	2	1	3	11.54%
	21-30	3	3	6	23.08%
	31-40	5	3	8	30.77%
	41-50	3	2	5	19.23%
	51-60	0	2	2	7.69%
	Over 61	1	1	2	7.69%
Gender	Male	9	7	16	61.53%
	Female	5	5	10	38.46%
Identity	Tourists	9	10	19	73.08%
	Citizens	2	1	3	11.54%
	Foreign workers or students	3	1	4	15.38%
Have previous AR Experience	Yes	12	11	23	88.46%
	No	2	1	3	11.53%

5.1.3 Experiment Set-Up

Before the participants start to use the application, they were told to click all the items like the information page, map page, and the interaction information box to make sure that they could see all the provided information. For the participants who have less AR experience, some basic instruction for how to make the augmented objects appear was given. In the beginning, they could choose the language they preferred. They spent about 3 to 5 minutes on average using the app to experience the AR reconstruction and understand the details of Prinzessturm. During the experiment, the participants could walk freely in front of the ruins of Prinzessturm to see the reconstruction from different distance and angles. After they finish the experience, they are asked to fill in the questionnaire. The first three questions are about the basic knowledge of AR experience and Munich. The questions were designed because they were related to the answers to other questions. There were 4 questions specifically related to the information about Prinzessturm. The answers to these questions were compared between the two groups to see the effectiveness of AR interaction. Other questions were the rating of the satisfaction, helpfulness and open questions about the advantages and disadvantages of the application. In addition to the survey with the questionnaire, interviews were conducted with the tour guides for the opinions from the expert side. The complete questionnaire for the survey and the interview can be found in the Appendix.

5.2 Evaluation Results

5.2.1 Questionnaire Analysis

The answers to the questionnaires were collected and organized afterwards. The first and the second question were for testing if the application could help enhance users' knowledge about Prinzessturm. The way that the users got informed of the answer to these two questions were the same, the information was provided at the information page. For the first question "When was Prinzessturm built?", the answer is in the 17th century. The percentage of the correct answers for group1 and group2 was 64.29% and 58.33%. For the second question "When was Prinzessturm torn down?", the answer is in the 19th century. The percentage of the correct answers for group1 and group2 was 64.29% and 75%. The percentage of group1 for both questions were the same, and the percentage of group2 for the second question was higher than the first question. In comparison with the group difference, group1 got higher percentages for the first question but got lower percentages for the second question. Overall, the percentages of the correct answers were nearly 60%.

The third and the forth questions were to compare the effectiveness of AR interaction between each group. For the third question "What is the nearest existed gate to Prinzessturm?", the answer is Isartor. The percentage of the correct answers for group1 and group2 was 85.71% and 66.67%. The percentage of group1 was higher than group2. While the users who gave wrong answers were all tourists and the amount for gorup1 and gorup2 were 2 and 4 respectively.

For the fourth question "What is the function of the window?", the answer is to place weapons. The percentage of the correct answers for both groups was 100%. The figure below shows the percentage of the correct answers for each question.

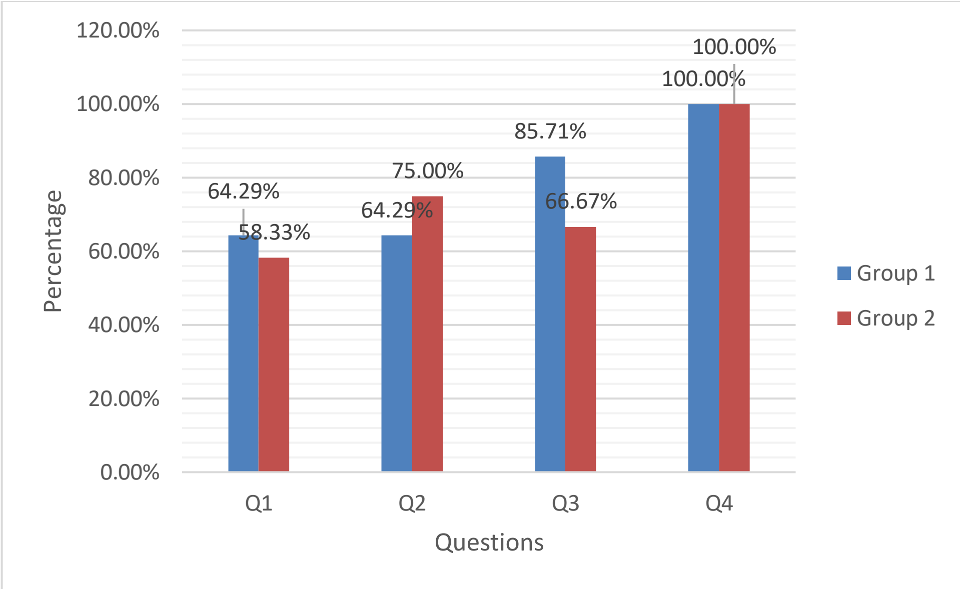


Figure 5-1 The percentage of the correct answers for Q1 to Q4

The result of the fifth question "How do you feel about this AR experience for reconstructing the tower?" is as Figure 5-2. For group1 with AR interaction, the percentage of "normal", "satisfied", and "very satisfied" were 14%, 50%, and 36% respectively. For group2 without AR interaction, the percentage of "normal", "satisfied", and "very satisfied" were 25%, 50%, and 25% respectively. In general, over 80% of users were satisfied with the application, and group1 had higher satisfaction.

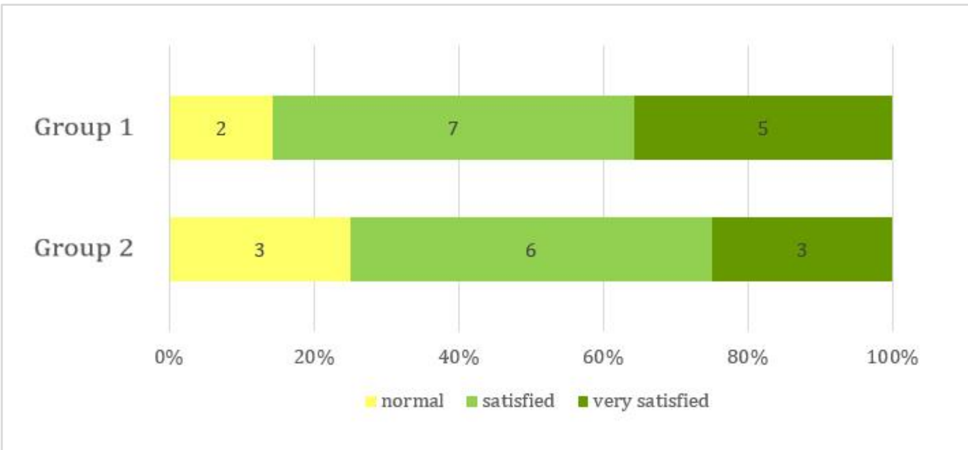


Figure 5-2 The satisfaction between the two groups

The result of the sixth question "How helpful is the highlight function for understanding the tower?" is as Figure 5-3. The percentage of the answer to "normal", "helpful", and "very helpful" was 21.4%, 42.9%, and 35.7% respectively. Nearly 80% of the users felt the highlight function helpful. The composition of gender and age group of the users of group1 was also analyzed. Among the users, over half of the female users thought the interaction is helpful and more male users chose very helpful in comparison with other choices. As for the age difference, the age group was divided into the users below and over 40 years old. The amount of “helpful” and “very helpful” was the same for the users over 40 years old, while there were three users below 40 years old felt “normal” to the AR interaction.

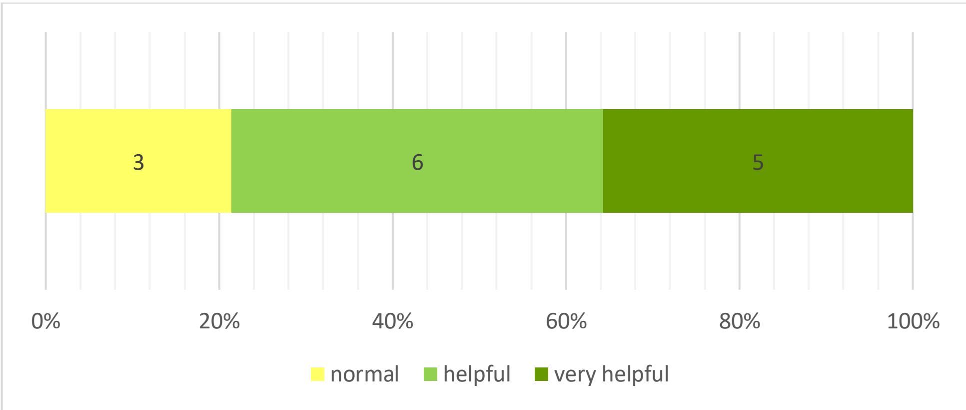


Figure 5-3 The helpfulness of the highlight function (group1)

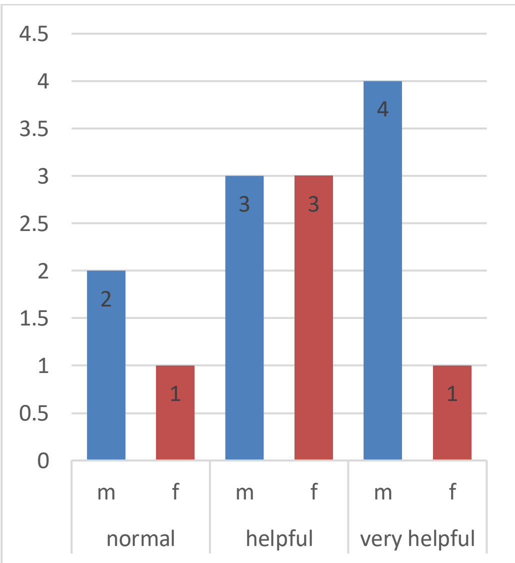


Figure 5-4 The gender distribution for helpfulness (group1)

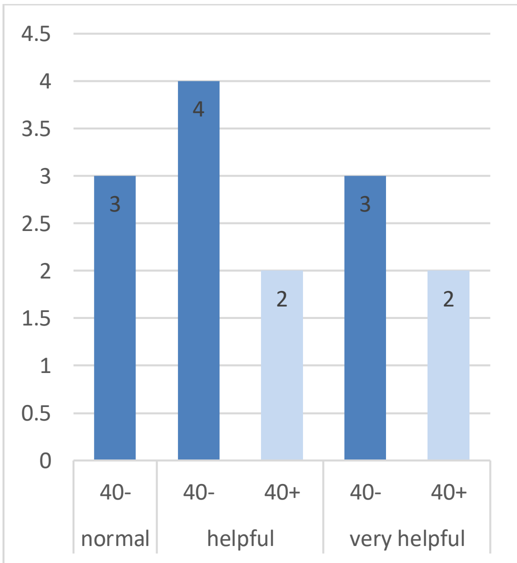


Figure 5-5 The age distribution for helpfulness (group1)

After the multiple choices, there were three open questions in the questionnaires about what they like, what problems happened and what can be improved about the application. Although nearly 90% of the users had previous AR experience, most of the experience was related to gaming, camera effect or other function. Rare experiences were for this kind of guiding function. For the question “What do you like about the app?”, many users thought that AR is a new technology and the integration of AR with guiding is impressive, interesting and attractive. Other answers were like “it can help understand the past of the ruins” and “it can make people understand the unpopular sightseeing spots”.

As for the problems they encountered during the testing, some people stated that the size of the texts could be bigger. The AR display was too big that filled the full screen when going too close to the ruin. It happened due to the big-size of the model and the limited space of the backyard. The display of the model would be more satisfying when keeping a certain distance to the ruins. At last, they described the improvement or the other function they would like to have as adding voice guide, gamification and the connection with other tourist spots.

Table 5-2 The results of the open question from the users

Questions	Answers
What do you like about the app?	• The integration of AR is interesting and attractive. • It is impressive to see the reconstruction model with the reality and the users can observe the object from different angles. • People can understand the appearance and the function of the ruin in the past. • Make people understand the unpopular sightseeing spots.
What problems happened when using the app?	• The texts can be bigger. • The performance was not good when going too close to the ruins because of the big-size of the model.
What can be improved? What else function would you like to have?	• Voice guides can be added. • The gamification of the application can make it more interesting and make learning through playing. • Connect the others ruins or missing buildings in Munich.

5.2.2 Interview

The expert-based interviews were conducted in person with two tour guides. Both of them mainly guide group tour through Europe and have over 3 years of working experience as tour guides. Thus, the interview could reflect the opinions from the perspective of the professional side. Each interview took 15 minutes. Both of them hold a positive attitude toward AR technology with reconstruction purpose. They thought the AR effect is really unique which overlays the virtual objects onto reality. It is easier for the visitors to imagine the picture of the past through AR than through oral guides or normal images. It can also be a nice tool for tour guides to display the AR effect by showing tablets to visitors. As more people prefer self-guided tours in comparison with guided tour, self-guided tourists can also use the mobile AR guide at their own pace. As for the essential parts of AR for reconstruction purpose, they thought that the position and the appearance of the model are important for displaying the past. About the application itself, they liked the impressive AR effect and the usage of the historical images to show how the tower was in the past. At last, they suggested that the application could be more multi-functional. It could include the combination of other tourist spots or the points that tourists need like transportation, banks, and restaurants. It can even provide the function of route planning.

Table 5-3 The results of the interviews with the experts

Questions	Answers
What is your opinion (attitude) toward AR reconstruction?	• Can be beneficial to tour guides and tourists
As a tour guide, what is essential to AR reconstruction?	• The position of the model • The appearance of the model
What do you like about the app?	• AR effect • The usage of historical images
What can be improved? What else function would you like to have?	• The combination of other tourist spots and tourism resources • Route planning

5.3 Discussion

From the results of the evaluation, it showed that the AR application can help enhance their understanding of Prinzessturm. Nearly over 60% of the users could answer the questions correctly after using the AR application. The percentage of the correct answers for the first and second question was lower than the expectation, maybe the question about the timing might be too detailed for the users to answer. For the question about the nearest gate, group1 was 20% higher than group2, while the percentage for the question of the function of the window was the same. The group difference of the third question was higher than the first and the second question, so it can be said that the AR interaction led to the different results. The same percentage for the fourth question might result from the problem of question design that the question was too easy. The results between the two groups were not very obvious, it might because of the problems of question design and the lack of samples. However, the contents of the questions were limited to the amount of information about Prinzessturm. About the satisfaction and the helpfulness of the AR interaction, over 80% of the users were satisfied with the AR experience. Nearly 80% of the users in group1 felt the interactive function helpful.

For the opinions from the users and the tour guides. All of them held positive attitudes toward mobile AR application for reconstruction purpose. They thought the experience was interesting and could help them understand the objects. Also, some problems with the texts and the AR display were pointed out from the users. The problem about the texts could be referred to the issue of AR interface. The problem could be reduced with the consideration of different age group or preference during the development. To reduce the problem about the field of view occurs with the relatively small screen size and when the distance between the users and the objects is short. A reminder of the distance for viewing the AR objects can be added to make the AR experience more satisfying. For the additional function for the AR application, the suggestion of combining related tourists spots and tourism resources was given.

6 Conclusion

With the booming development of mobile AR, the value of AR effects for the field like cultural heritage and tourism have been identified from the previous researches. However, there was no discussion about the design guidelines for AR reconstruction. This thesis research attempted to develop a set of design guidelines for AR reconstruction. To explore the components of the guidelines, the features and the development of AR technology and related applications were identified in the beginning. Then the 6 guidelines about **suitable tracking method**, **quality 3D models**, **AR interaction versus non-interaction**, **storytelling**, **provide user guide and feedback**, and **prevent cognition overload** were generated through the summarization of the above findings. Also, an evaluation was conducted through on-site user tests of the mobile AR application which was implemented with the new design guidelines. The following will first answer the research questions and describe the outlook on future work.

6.1 Summary

A. What is special to AR applications for AR reconstruction? How to identify the features of AR reconstruction?

The special feature of AR applications for reconstruction purpose lies in high requirements of the superimposition of the virtual objects to the reality. Thus, the users can enjoy the immersive AR experience as if the reconstruction model was rebuilt at the same location. To achieve the effect, the tracking and registration of the virtual model are important. Besides, the emphasis on reconstruction and exhibition purpose requires suitable explanations to tell the stories. The use of interaction and multimedia can make AR applications more appealing. To identify the features, this research initiated from summarizing AR technique like tracking, interaction, and visualization.

B. How to develop the guidelines? What should be included within the guidelines?

To develop the guidelines, every perspective of AR must be considered. From the state of ar for AR reconstruction and the summarization of existing AR design principles, researches, and applications. Then the final guidelines were generated from the above findings. The scope of the proposed guidelines include the aspects from the AR technique, content, and the consideration of the AR interface.

C. **How to develop the prototype? How to integrate the proposed guidelines?**

One of the difficulties at the beginning of the research is to find an appropriate site to demonstrate the proposed guidelines. Fortunately, the ruin of Prinzessturm which is in the center of Munich city was preserved. The location is ideal for the thesis research because ruins and archaeological sites are usually found in distant rural areas which could cause the inconvenience for the research. The prototype was developed by Unity with some basic function and the integration of the guidelines with the application can refer to Table 4-1.

D. **How to design the evaluation experiment? How helpful are the proposed design guidelines?**

The evaluation was conducted with user tests and interviews with experts. The questionnaire for the experiments included the questions to test whether the users could understand the information about Prinzessurm and some opinions toward the AR application. Nearly 60% of the users could answer the questions correctly and about 80% of the users were satisfied and felt interesting and impressive to the application. The value of the effects of AR reconstruction was also agreed with the tour guides. However, there was no significant difference between the tests of AR interaction and non-interaction.

6.2 Outlook

This thesis is one of the first researches about design guidelines for AR reconstruction. Through developing the guidelines, the research identified and summarized the special features and related current design principles for AR reconstruction. It can be the start point for the developers to design mobile AR reconstruction and provide a basic reference for them to follow. The significance is to assist digital heritages to arouse public awareness and appreciation of heritage sites. The evaluation showed that the guidelines can enhance users' understanding of the reconstruction. Most of the users were satisfied and felt interesting with the AR application which was implemented with the proposed design guidelines. The results also showed the difference between the group with AR interaction and non-interaction, while more samples and further research would be needed to examine the exact effectiveness of AR interaction.

One of the limitations is the rare documents of Prinzessturm. The proposed guidelines can be further evaluated at different heritage sites where there are more stories to tell. In addition, the gamification of the AR interaction can be one of the further direction of development since gamification can be regarded as the advanced interaction. As mobile AR technology is getting more mature, AR gaming will be more popular and prevailed. The integration of gaming with AR reconstruction can make learning through play and enhance user motivation. The combination of other reconstruction sites can make the application more informative and allow more comprehensive researches.

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Appendix

Questionnaire

Age: ☐ 20↓ ☐ 21-30 ☐ 31-40 ☐ 41-50 ☐ 51-60 ☐ 61↑

Gender: ☐ male ☐ female ☐ other

You are a: ☐ tourist ☐ citizen ☐ other________________

- How is your previous experience with AR?

Have no experience	0	1	2	3	4	5	Very experienced

- How are you familiar with Munich?

Not familiar	0	1	2	3	4	5	Very familiar

- Did you have previous knowledge about Prinzessturm? ☐ Yes / ☐ No

1. When was Prinzessturm built?
   ☐ 16 century ☐ 18 century ☐ 20 century
2. When was Prinzessturm torn down?
   ☐ 18 century ☐ 19 century ☐ 20 century
3. What is the nearest existed gate to Prinzessturm?
   ☐ Isartor ☐ Sendlinger Tor ☐ Karlstor
4. What is the function of the window?
   ☐ to see the view ☐ to place weapons ☐ for ventilation
5. How do you feel about this AR experience for reconstructing the tower?
   ☐ very unsatisfied ☐ unsatisfied ☐ normal ☐ satisfied ☐ very satisfied
6. How helpful is the highlight function for understanding the tower?
   ☐ not very helpful ☐ not helpful ☐ normal ☐ helpful ☐ very helpful
7. What do you like about the app?
8. What problems happened when using the app?
9. What can be improved? / What else function would you like to have?

问卷 (Questionnaire in Chinese)

年龄： ☐ 20↓ ☐ 21-30 ☐ 31-40 ☐ 41-50 ☐ 51-60 ☐ 61↑

性别： ☐ 男性 ☐ 女性 ☐ 其他

您是： ☐ 游客 ☐ 市民 ☐ 其他________________

- 你有使用過 AR 的经验吗?

	0	1	2	3	4	5	
没有经验							非常有经验

- 你对慕尼黑有多少认识?

	0	1	2	3	4	5	
不了解							非常了解

- 你知道"公主塔"吗？ ☐ 知道 / ☐ 不知道

1. "公主塔" 兴建于什么时候？
   ☐ 16 世纪 ☐ 18 世纪 ☐ 20 世纪

2. "公主塔" 在什么时候被拆除?
   ☐ 18 世纪 ☐ 19 世纪 ☐ 20 世纪

3. 下列哪一个城门最靠近 "公主塔" ？
   ☐ 伊萨门 Isartor ☐ 森德灵门 Sendlinger Tor ☐ 卡尔门 Karlstor

4. 请问塔上的窗户有什么功能？
   ☐ 看风景 ☐ 放置武器 ☐ 通风

5. 请问您对此应用程序的满意度如何？
   ☐ 非常不满意 ☐ 不满意 ☐普通 ☐满意 ☐ 非常满意

6. 请问您觉得 "变色强调的互动功能" 对于理解公主塔有帮助吗？
   ☐ 非常没有帮助 ☐没有帮助 ☐普通 ☐有帮助 ☐非常有帮助

7. 您喜欢这个应用程序的什么地方？
8. 在使用此应用程序时有发生什么问题？
9. 有什么可以改进的地方? / 您觉得还可以增添什么功能？

Interview Questions For Experts

1. What is your opinion (attitude) toward apps for AR reconstruction?
2. As a tour guide, what is essential to apps for AR reconstruction?
3. What do you like about the app?
4. What problems happened when using the app?
5. What can be improved? / What else function would you like to have?