DEPARTMENT OF INFORMATICS

TECHNISCHE UNIVERSITÄT MÜNCHEN

Master's Thesis in Informatics: Games Engineering

ARtemis - Augmented Reality and Ancient Statues

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ARtemis - Erweiterte Realität und Antike Statuen

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I confirm that this master's thesis in informatics: games engineering is my own work and I have documented all sources and material used.

Munich, 15.06.2019 Michael Felleisen

Abstract

In times of extreme quantities of accessable entertainment online, museums struggle to keep their visitors interested and entertained.
In this thesis we will explore, in collaboration with the 'Abgussmuseum' Munich, if it is possible to add value to the visitor experience with an augmented reality serious game application for a special exhibition in 2019. In addition, we will use concepts and functionalities of three previous bachelor theses and thereby create a basis for further work in this museum.

Kurzfassung

In Zeiten von extremer Mengen an zugänglicher Unterhaltung im Internet, kämpfen Museen darum, viele neue Besucher anzulocken.
In dieser Masterarbeit werden wir in Zusammenarbeit mit dem Abgussmuseum München untersuchen, ob es durch eine Augmented Reality Serious-Game-Anwendung für eine Sonderausstellung im Jahr 2019 möglich ist, einen Mehrwert für das Besuchererlebnis zu schaffen. Zudem werden wir versuchen auf 3 vorhergegangenden Bachelorarbeiten aufzubauen, möglichst viele Funktionalitäten übernehmen und so eine Basis für weitere Arbeiten in diesem Museum zu schaffen.

Contents

1. Introduction

Museums have existed for more than 2000 years. Over the centuries the concept of museums has spread all over the globe and there is hardly any country left today, no matter how small it may be, that does not have a museum.
Traditionally, the task of a museum is to collect, preserve and research objects of cultural, religious and historical relevance. Furthermore, a museum has the responsibility to present its collection to the public.[1]
This task has changed in recent years. In the rapidly changing world of the Internet, museums with their information panels and gradually changing exhibitions are slowly but surely being left behind.
Nevertheless, the number of museum visits between 1995 and 2017 has increased more or less steadily, despite the boring reputation museums enjoy especially amongst teenagers.
As reasons for the increase in visitor numbers, the museums themselves reported special exhibitions, special events and intensified public relations work.
Overall, the number of visitors has risen sharply in 18.1% of all museums. A significant decline in the number of visitors can be observed in about one fifth of all museums.
This is mostly due to the end of special exhibitions, fewer special exhibitions and renovation work. Apps are rarely used in museums. In 2017, only 7.1% of all museums surveyed used apps in their exhibitions. However, computer-aided programs are already used by 18.2% of all museums.[2]
Since computers and especially smartphones are an indispensable part of almost every adult's everyday life, it could be that these types of media in particular arouse more interest than conventional media.
In addition, the possibilities of a museum to show and explain certain things through apps and computer programs are much less restricted than with conventional media.
Therefore we will try to show how the famous Laokoon group is composed of its eight individual parts. An effort that can even be done interactively.
Furthermore, we will try to lay the foundation for other university projects by creating an easily extensible and durable app framework.
And perhaps this or a project based on this will be part of the next special exhibition of the cast museum in Munich.

2. Museum for Casts of Classical Works of Art Munich

2.1. History

Since 1865 the LMU Munich has had a Chair of Classical Archaeology.
For the first time, the research and maintenance of the original casts was to be carried out by experts. The German archaeologist Heinrich Brunn was appointed from Rome to take over these tasks.
In 1877 the collection was stored with meanwhile 379 casts at the Numismatic Collection in the former Jesuit College near St. Michael.
Little by little Brunn acquired further premises in the northern courtyard arcades of the Residenz. 1932 they finally moved into their new home. 1944 during the second world war, all 2398 casts fell victim to an Allied bombing raid.
More than 30 years later in 1976, under the leadership of Paul Zanker, the museum was rebuilt.
The museum as it is now, has only existed for 30 years and with around 2000 casts, is once again one of the four largest collections in Germany.[3]

2.2. Collaborations

The museum is very involved in cooperation with a wide range of partners. In 2019 a multimedia guide for 10 statues was created together with the University of Augsburg and the BR-Studio Schwaben.
Various projects and seminars were developed in cooperation with the TUM and the LMU.
In 2017, shortly before Christmas, a seminar for pupils was offered to design parts of an augmented reality app and in the end they were able to see some of their ideas implemented.
Practical courses of the TUM also work together with the museum to make future exhibitions even more interesting.
Furthermore, some students are currently working on making it possible to paint a statue indirectly on a computer. The painted areas will then be projected onto the target statue using a projector, just to name a few examples.

Figure 2.1.: Northern Atrium.[3]

But the museum does not only cooperate with universities. In 2019, for example, an episode of ZDF's *Der Alte* was released, some of which was filmed in the museum. Also in 2019 the rap artist Shirin David released her single *ICE* and parts of the music video were also shot in the museum.

3. Related Work

3.1. Bavaria National Museum

In 2014 an exhibition supported by augmented reality was offered in the Bavarian National Museum. Five different exhibits offered augmentations that visitors could view on their tablets or Google Glasses. One augmented statue was made around 1460 - 1531 in Würzburg by Tilman Riemenschneider. The statue depicts a naked Mary Magdalene with hair all over her body. In 1756 the statue was removed from its original altar as it was considered offensive and replaced with a dressed version.[4] Today, with the help of augmented reality, the museum is trying to return the statue to its original place by augmenting the altar around the statue.
Furthermore virtual inscriptions were faded in for a model of the historic city center Munich and another statue. In addition, non- augmented information texts, detailed audio guides and embedded videos were provided by the app.
There was even a two dimensional map of the exhibition area to help with orientation.[5]

(a) Augmented Altar [5]

(b) Augmented Map [5]

Figure 3.1.: Bavaria National Museum

The app was developed in cooperation with the company Metaio GmbH.
The company was founded in Munich in 2003 and acquired by Apple in 2015. [6][7] They even

offer their own pattern tracking SDK, which is able to track ID markers and picture markers. Furthermore it can use 3D SLAM tracking, CAD based 3D tracking and face tracking. [8] This means that the SDK is almost as powerful as the Vuforia framework we use and is supported on Android, iOS and Windows.

3.2. Eskenazi Art Museum

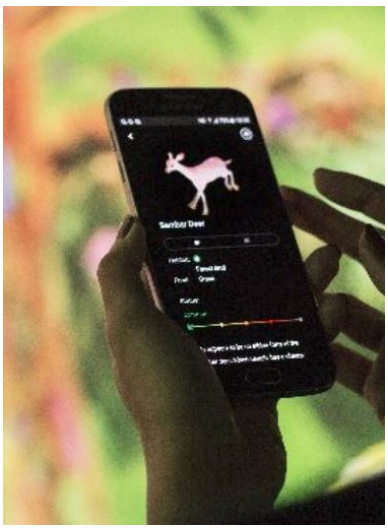
In 2018 a small experiment took place at the Eskenazi Art Museum at Indiana University. The team tried to augment an exhibit with augmented reality and the Microsoft HoloLens. The selected statue was a copy of the Resting Satyr.
In the beginning the team wanted to offer a large number of animations to the visitors and bring the statues to life. However, that idea was discarded due to technical limitations of the HoloLens and the immense amounts of work necessary to complete the animations. Also there were many problems with the very small field of view. Another idea was that virtual statues should lead the visitors to the real statues. It was also planned to draw virtual walls into the exhibition rooms and let the visitor walk through virtual doors. The problem was that the visitors would see very little of their actual surroundings. So accidental collisions with statues would be absolutely possible.
Finally, a possible reconstruction of the statue was shown to the right of the original. On the left you could see two alternative variants of preserved statues. To anchor the reconstructions in 3D space, they used the original statue as a 3D model target. Several audio guides and two display boards with information texts were provided as well.[9]
Interesting was the gaze control to interact with buttons. The visitor had to look at a button for a certain time to activate it.

Figure 3.2.: Original Statue in the Middle, Augmentations on both Sides

3.3. National Museum of Singapore

The Story of the Forest special exhibition of the National Museum of Singapore tried to make a visit to their museum more interactive and fun for children.
With the help of the mobile phone camera, different plants and animals must be found within the animated walls. If photographed, the found plants and animals are added to a personal collection. In your collection, you can read more interesting information about the animals and plants. [10]
Similar to Pokemon Go, the gameplay is a bit more interactive in contrast to most other augmented reality applications made by museums.

(a) Photographing the Animal [11]



(b) Animal Collection[11]

Figure 3.3.: National Museum of Singapore

3.4. Erlangen-Nuremberg's Antique and Classical Collection

Unlike the previous examples, this project has nothing to do with smartphones. The Friedrich-Alexander-University in collaboration with the Antique and Classical Collection in Erlangen-Nuremberg recoloured a cast of an Augustus statue.
The team created a fully automated calibration algorithm for multi-projection mapping on 3D object surfaces. They achieved extremely accurate results with only consumer-grade hardware. Using projectors, they gave the statue its original colour back.
Just like our project, they needed a precise 3D model to track the statue. Since they additionally used a structured-light scan to generate the tracking depth data, their scope of application is limited to opaque, white objects.[12] And casts are exactly that.
The advantages for visitors would be that they would not have to have a current smartphone or download an app to visit the museum. The disadvantage for the museum is that they have to provide quite expensive hardware to use this technology.

(a) Projected Colour [12]

(b) Object's Position Estimation[12]

Figure 3.4.: Augustus Statue

4. Model Creation

4.1. Photography

Due to the lack of professional camera equipment we used fairly high end smartphone cameras to take the pictures for the model creation.
The Huawei Mate 10 Pro's Leica dual camera setup with 12-megapixels rear camera was able to produce fairly high quality pictures. Under certain circumstances, the resulting images may even be better than the images from a standalone SLR camera because we didn't have much experience with photography.
Furthermore, the lighting conditions during image taking were sometimes very poor so that the automatic image processing of the smartphone and the resulting brightness adjustments certainly had a positive effect on the end result.

(a) Lighting and Space Conditions

(b) Laokoon Torso on a Crane

Figure 4.1.: Two pictures of the attic

The reasons for the complicated conditions for photographing were the relatively poorly lit attic of the museum and the lack of space to position oneself correctly to photograph the object from all desired angles as can be seen in Fig 4.1 a).
The large differences in brightness in the pictures were caused by the adjoining atrium and created, depending on weather and season, one side with very high brightness conditions and another side with very low brightness conditions.
Another problem was the milky glass front that separated the attic from the atrium and was in a fair amount of pictures per object. Unfortunately reflecting surfaces can lead to significantly worse results in photogrammetry.
Since the casts were only allowed to be handled by professionals, several parts of the Laokoon group had to be photographed from multiple sides on different dates.
Because with the usual photogrammetry procedures, objects should not be moved during photography sessions, several pieces of the statue were split into front and back parts, only to be manually stitched together again in the end.
In the special case of the Laokoon torso we faced even more limitations. We were interested in the underside of the statue to learn how the torso was connected to the altar piece underneath. Therefore the torso had to be lifted with a mobile crane to make the underside of the original casting visible as you can see in Fig. 4.1 b).
Because we were not even allowed to touch the statue parts, the torso had to be hung by a special employee of the museum.
Due to the comparatively low ceiling height of the attic and the special suspension of the statue to avoid damage, the statue only hung at a height of about 30-40 cm, which restricted photographing and navigating beneath the statue.
Nevertheless it was possible to take sufficient pictures of almost all parts of the Laokoon group.

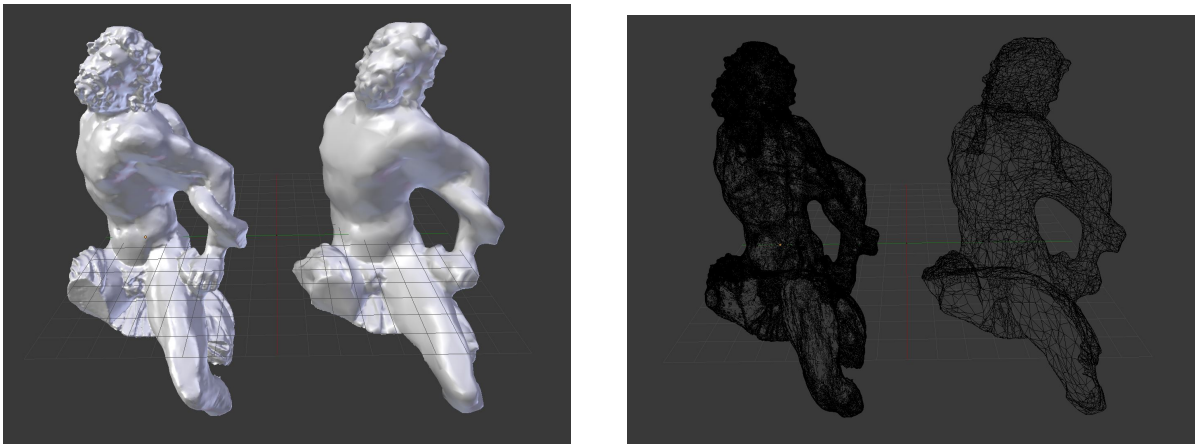
4.2. Photogrammetry

To get 3D models from the taken photos we used Autodesk Recap Photo with an educational license. Autodesk Recap Photo is a centralized and monetarized photogrammetry service.
To get the desired 3D models you can upload up to 100 photos per model to the Autodesk servers.
They take the 2D images and look for similar image points or contrast points. All images have to be connected through such points or the images you uploaded are not used properly. This should not be a problem if you took the photos in a small enough angle relative to each other. Through the points on the images a 3D point cloud is generated and connected as a convex hull.
The texture is applied by cutting the 2D images between points and applying it to the mesh via UV mapping. All this results in a very clear model of the object and an unclear model of the surrounding space as seen in Fig 4.2.
When the processing of the model is finished, you can download it locally to your computer.

Figure 4.2.: 3D Model of Laokoon Torso and Surroundings.

4.3. Model Processing

The resulting models have a very high vertices count at around 500.000 after the irrelevant parts of the model have been cut away.
This always included the space around the statue and with several models per statue piece also the blurred or non-existent side, which could not be photographed.
The model cutting can be done in a separate program like Blender or in the included model viewer from Autodesk.
Advantages of the built-in model viewer is that it is very easy to use. Other advantages only come into effect when combined with the Unity Engine.
If a high-resolution camera was used when taking photos, the resulting textures with a resolution of 8192 x 8192 pixels are way to big for practical use in generic game engines. The maximum texture size of Unity is 2048 x 2048 pixels.
This means that Unity compresses the statue textures after importing by a factor of 16, which results in a very blurry result.
The resulting model quality was not acceptable which means we could not use the original photographed textures of the statue pieces.
Luckily the statues are pretty much plain white which makes it easier to reconstruct a realistic coloring.
A disadvantage of the built-in model viewer is the relatively bad vertices decimation algorithm compared to the Blender capabilities. This makes sense because the built-in variant is optimized for the combination of the low-polygon model and a very high resolution texture. By exporting the models in the .fbx format with a texture resolution of 2048 x 2048, we could still profit from the very good UV-Mapping algorithm from the built-in viewer.
In Blender the vertices count was reduced from approx. 500.000 to approx. 10.000 - 20.000 depending on the statue piece to make it easier for smartphones to run the application.

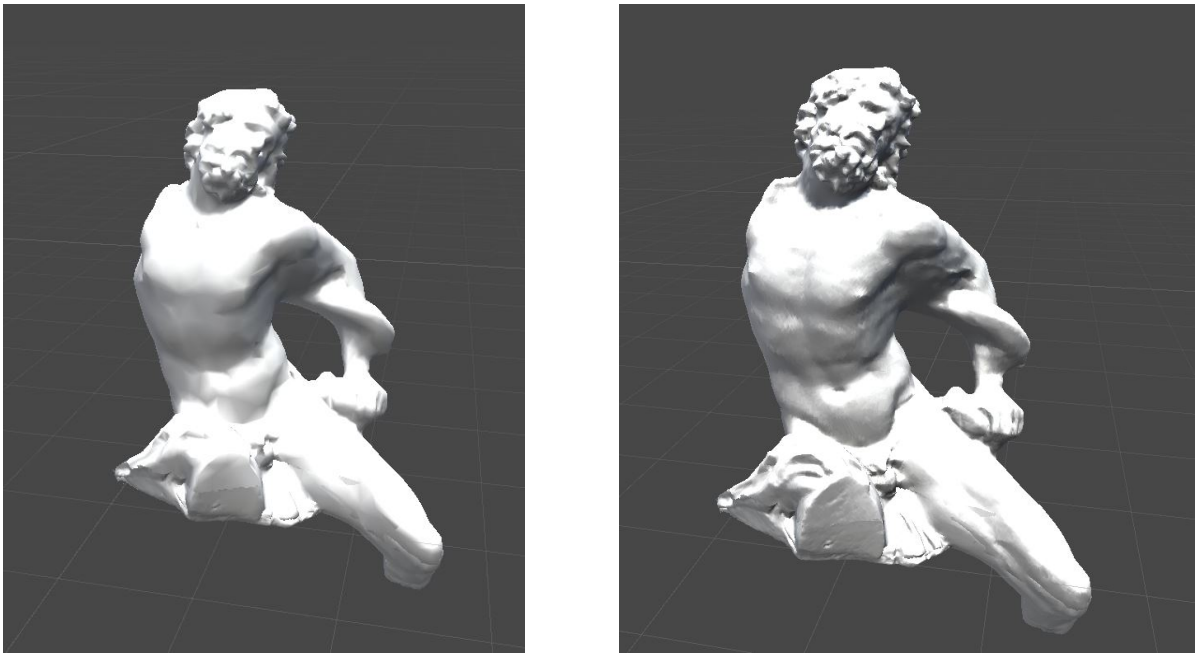


(a) High-Poly left, Low-Poly right

(b) Wireframe Comparison

Figure 4.3.: Vertices Count Comparison

After that we manually baked the normals and the ambient occlusion of the high-polygon model on the low-polygon models to make up for the vertex count difference.
Those textures were calculated at a resolution of 2048 x 2048 to get the maximum amount of details from the high-polygon models.
In the end we could simply import the models and newly generated textures into Unity and use a standard illumination shader to generate realistic shadow casting.



(a) Low-Poly, no Normal Map, no Occlusion map

(b) Low-Poly, with Normal Map and Occlusion map

Figure 4.4.: Mapping Comparison in Unity

5. Application Features

5.1. Minimap

Because it can be very difficult to orientate oneself in the museum, we wanted to try to help the visitors by providing some kind of map.
The first method that comes to mind would be to display a simple 2D floor plan in the app. However, this idea is by no means innovative in any way and was therefore replaced by a 3D view of the museum.
This way every floor is visible at all times and represented by transparent planes. This could be an advantage compared to traditional 2D maps, as it is much easier to see on which floor the target is located.
Only the floor you selected is displayed as opaque. Icons can be placed at important locations that are relevant to the visitors, such as entrances and exits to the museum as well as information about stairs, elevators, toilets and even statue locations.
This has a very great benefit because it can be very difficult to find certain statues in this museum.
Through the statue selection screen it is possible to simply click on a statue name the visitor is interested in, read a small information text and directly switch back to the minimap screen where the current location of the statue is revealed.
This is made possible by an easy-to-manage JSON file in which the statue positions could be updated if the statue's position changes over time. Since the museum is highly flexible and constantly moves statues around the easy maintainability is very important.

In the beginning, the idea was discussed to let the Minimap rotate automatically by using the built-in compass capabilites of smartphones and tablets.
This idea was quickly discarded because the compass data was not accurate enough and the relatively slow update of the compass direction made reading the map extremely difficult and confusing, even for very experienced smartphone and tablet users.
The rather slow update rate came from the smoothing process that had to be used on the compass data to combat the heavy direction fluctuations. The average of approx. 30 compass values yielded very smooth and accurate results at the cost of speed.
GPS tracking inside of the museum was unfortunately not possible. Therefore the Minimap does not show the visitor's own position.
The interesting thing about the Minimap from the Unity point of view is that it is a 3D object in a 2D GUI.
A second camera renders the minimap to a RenderTexture, which is then inserted into the GUI as a 2D image.

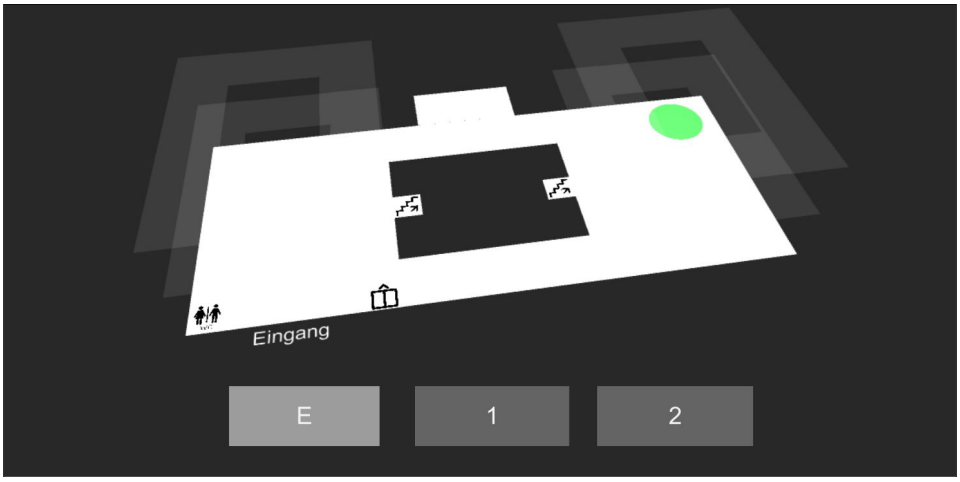


Figure 5.1.: 3D Minimap with Statue Target in 1st Floor

The automatic scaling of the RenderTexture on the GUI layer was an interesting challenge and shows that the GUI capabilities of the Unity Engine is one of its weaker areas.

5.2. Statue Collection

In the statue selection it is possible to choose from a large number of statues. If the user decides on a certain statue and clicks on it, he is brought to a small information screen as can be seen in Fig 5.2.
Here the user can read a few sentences about the statue to get a rough overview.
If there is further interest, it is possible to get more information in the Internet at the push of a button.
This is similar to the new media style, which also has a two-staged information system with headlines and the corresponding articles.
In doing so, visitors can learn more about the statues without feeling overwhelmed by text and still have the benefits of being able to read everything about a subject if they choose to do so.
This part of the app is also usable outside the museum location.
As described in the Minimap section it is also available to press a button to display the position of the statue within the museum.
To further assist the museum visitor in finding the statue, a picture or 3D model of the statue is displayed next to the information text.
The loaded picture, the information text itself and the online link to more external websites are stored in a JSON file and can be changed very easily.

Figure 5.2.: Information Screen, Example: Aphrodite

5.3. Help Screen

The Help Screen lists the museum's contact details and address.
Furthermore, a button in the application makes it easy to access the museum website to find the latest information about current exhibitions and guided tours.
This could be important if a user finds the app in the Google Playstore without knowing that it belongs to this particular museum.

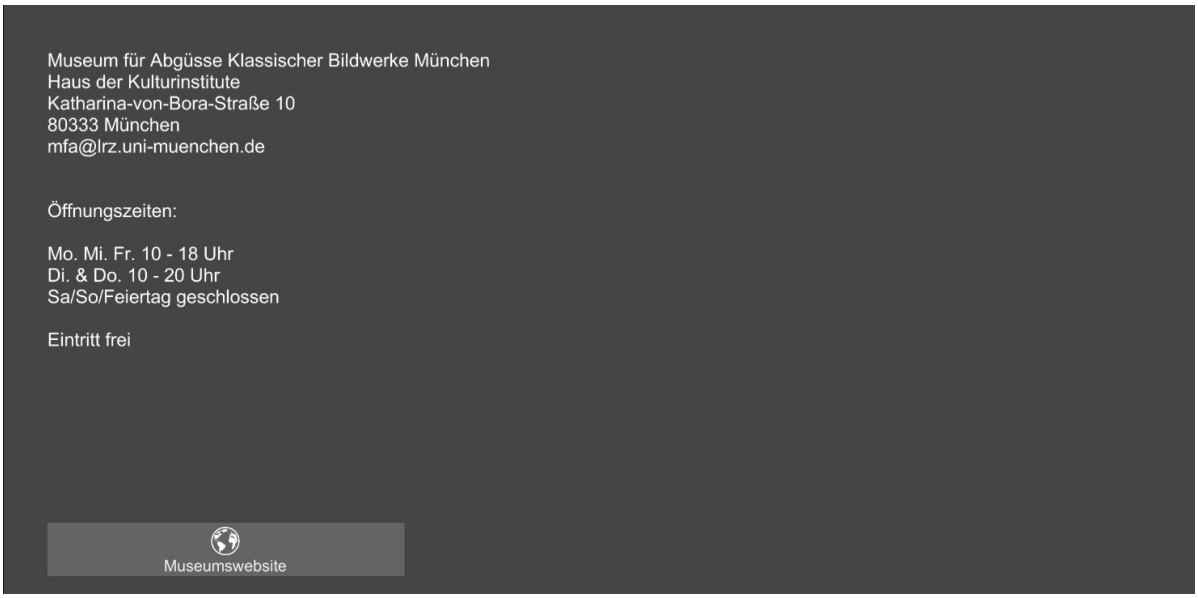


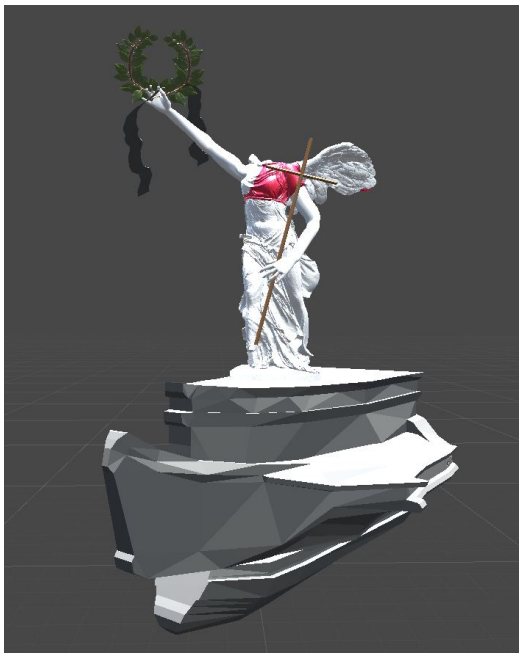
Figure 5.3.: Help Screen

5.4. Statues

5.4.1. The Winged Nike

The Winged Nike, The Winged Victory of Samothrace or the Nike of Samothrace is a sculpture of the ancient Greek god Nike who personified victory.
It was probably built around 190 BC and was found in the Kabir shrine on the Greek island of Samothrace between 1863 and 1879.
Here, not only artificially restored parts of the statue can be marked by augmented reality directly at the statue. Other replicated parts can be displayed, such as arms, various carried items and the lost base of the statue, the Prora.
The features around this statue were part of Elisabeth Fraberger's bachelor thesis.[13]

(a) Original Cast



(b) Statue with Digital Reconstructions and Additions

Figure 5.4.: The Winged Nike

5.4.2. The Crouching Aphrodite & Athena Parthenos

The Crouching Aphrodite was a bronze statue dating back to about 250 BC.
It depicts the ancient Greek goddess Aphrodite associated with love, beauty, pleasure, passion and procreation. Since large parts of the statue like the arms and the head are no longer existing, the app tries to show missing parts by augmented reality.

(a) Raw 3D Model (b) Statue with Digital Reconstructions

Figure 5.5.: Crouching Aphrodite

A Roman miniature reproduction of the famous statue that Phidias made for the Partheon in Athens. Created between 120 - 150 A.D., made of marble measuring 98cm x 36cm.
Similar to the Crouching Aphrodite, various parts are missing from the original. The replica in the museum shows the statue completely, therefore the app colors both arms, parts of the helmet decoration and the worn shield light blue to mark the replications.
Furthermore a spear, which the statue presumably held in the right hand, can be faded in by the app. A small AR information text to the right of the statue gives the visitor some details.
Both statues originate from Christian König's bachelor thesis and were extracted and transferred into this thesis project.[14]

Figure 5.6.: Athena Parthenos

5.4.3. Aphaia, West Pediment of the Temple of Aphaia

(a) Source: Bunte Götter [15] p. 97

(b) Digitally Painted, no Artist

Figure 5.7.: Aphaia

The statue was located at the Temple of Aphaia on a hilltop on the Greek island of Aegina. The goal of this feature was to show how colorfully the statues were painted at that time. This is hard to imagine if you can only see the completely white casts in the museum.
In addition, this feature should be an alternative to the costly painting of statues, since we only need a 3D model of the statue itself and then have to paint it historically correct.
This saves the step of having to physically copy the statue.
The Aphaia statue was chosen because it is one of the two existing statues from the Aphaia Temple in the museum and these are very well researched regarding their ancient colouring. How exactly the statue was perhaps painted we took from the book Bunte Götter[15]. Unfortunately the tracking didn't work very well with the statue.
In addition, the resolution of the texture was too low compared to the detail that would have been necessary to exactly copy the ornamental painting provided by the source material.
One could use multiple textures for the model to increase the resolution at the important painted places and leave the painting to an artist with a lot more talent. All that could significantly increase the artistic and educational value of this feature.

5.4.4. Laokoon and His Sons

The Laokoon group is intended to be the core of the application. The Laokoon group is the most important representation of the death struggle of Laokoon and his sons and one of the most important statues of the antiquity that have survived today.
It was probably created around 200 B.C. as a bronze statue which might have sealed its demise. The original was possibly melted down in wartime and was lost forever.
The first time the statue is mentioned by Pliny the Elder, who saw the masterpiece in the residence of Titus, calls it a statue *ex uno lapide*. A statue made from a single stone.
This is not true for the Laokoon group found in 1506.
Pliny the Elder probably described the statue as *ex uno lapide* because the intersections between the individual parts were so cleverly concealed that they were hardly visible.[16]
Another mystery about the statue revolves around the right arm of Laokoon. Probably the most controversial part of the statue group. When the statue group was discovered in 1506, the arm was not under the recovered parts. Giovanni Angelo Montorsoli, a pupil of Michelangelo, was commissioned to complete the statue again. He completed the arm powerfully stretched as seen in Fig. 5.8. In 1903, almost 400 years later, the missing right arm of Laokoon was found in a stonemason's workshop. However, the arm was strongly angled and took the powerful gesture from the Laokoon, which had previously been decisive for interpreters.[17]
The statue was to become one of the cornerstones of today's famous Vatican Museum.

Figure 5.8.: Laokoon Puzzle Game

Today the statue consists of 8 individual parts, the Laokoon torso, the left son, the right son, the altar, the Laokoon right arm, the Laokoon left leg, the right shoulder of the left son and another small altar piece.
In the app itself you can do different things with the statue. On the one hand it is possible to click on the different parts of the statue. After that the user can take a closer look at the individual parts by using the zoom and rotation functionalities. This provides an added value especially for the Laokoon torso, as you can see very well how the part was originally attached to the altar. Once a piece is selected, the user no longer has to point the tablet at the statue and can comfortably read through the information text and examine the statue part, because it is no longer in augmented reality space.

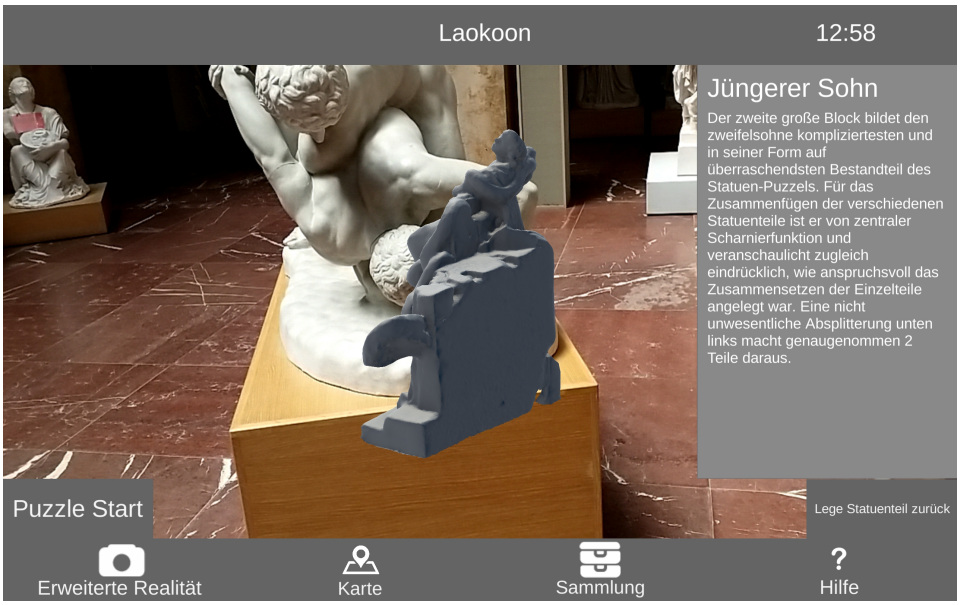


Figure 5.9.: The Younger Son of Laokoon in Free Inspection Mode

To give the whole thing a playful touch it is possible to let the statue explode into its individual parts. After that the user has to bring the parts back to their actual place via touchscreen. This makes it particularly clear that the statue consists of many different parts. Beyond the normal puzzle mode, there were ideas not only to shift the puzzle pieces randomly in different directions, but also to give them random rotation. However, this caused many problems on the user side.
To be able to orient 3D objects accurately in augmented reality space on a tablet one would probably have to limit the rotation to one axis. In order to not make the whole thing much more counterintuitive, the idea was to use two finger touch gestures for the rotation and one finger for the displacement. But in testing, the two-finger spinning motion was really unpleasant in its execution, because you still had to hold the tablet with one hand and point at the statue at the same time.
Information given in the app was taken from the exhibition catalogue of a Laokoon exhibition in Berlin.[17]

5.5. Modularity, Extensibility and Durability

The application designed for easy expandability. Due to a very modular structure of the source code and the structure within Unity it is very easy to add new features.
The UI, which conceptually is based on Gilles Tanson's bachelor thesis, is also entirely flexible. Furthermore, a large amount of textures from his project were reused our app.[18] Due to some changes it now works with all common smartphone and tablet resolutions in vertical and horizontal mode.
With this and Unity, the application can be run on almost every smartphone and tablet, in every available resolution.
Vertical and horizontal use are equally supported. All this was necessary because the app is planned as a basis for other bachelor's and master's theses.
Furthermore, we have tried to use as few code libraries as possible to prevent that parts of the program will not work any more due to discontinued support.
So the only external library we use is Vuforia, to facilitate the tracking of statues and since they are currently working very closely with Unity, the likelihood of support in the future is quite high.

6. User Study

The application was tested in a user study with a total of 20 participants. Most of the participants were on site at the museum, a small fraction tested the app at home with provided pictures of the relevant parts of the museum.
For questions concerning an assessment of a certain matter we use the Likert scale.
In general, the data was evaluated in such a way that the category *strongly agree* was given 5 points and the category *strongly disagree* was given 1 point.
Overall, all Likert scale questions had 5 options and thus a neutral center.

6.1. Participant Data

6.1.1. Age and Gender

The 20 participants were on average 31.65 years old. 13 participants were men and 7 were women. 70% were 27 years old or younger.

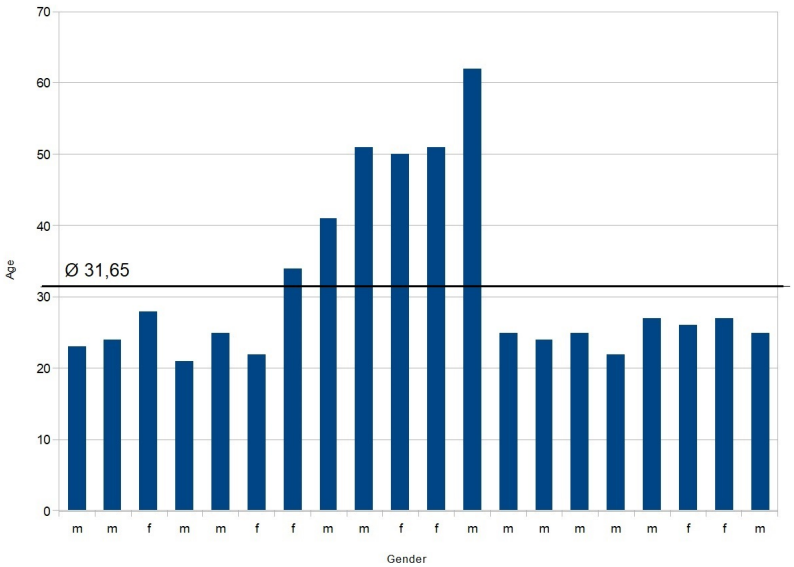


Figure 6.1.: Age & Gender

6.1.2. Previous Knowledge

Here the participants were asked whether they were familiar with Greek and Roman mythology. With an average score of 2.7 points the participants tend to say that they are not familiar with Greek and Roman mythology.
The second question asked whether the participants were well versed with augmented reality. With an average value of 3.6, the participants are more familiar with augmented reality.
From the data it can be observed that the older a participant is, the less likely it is that they will be familiar with augmented reality.

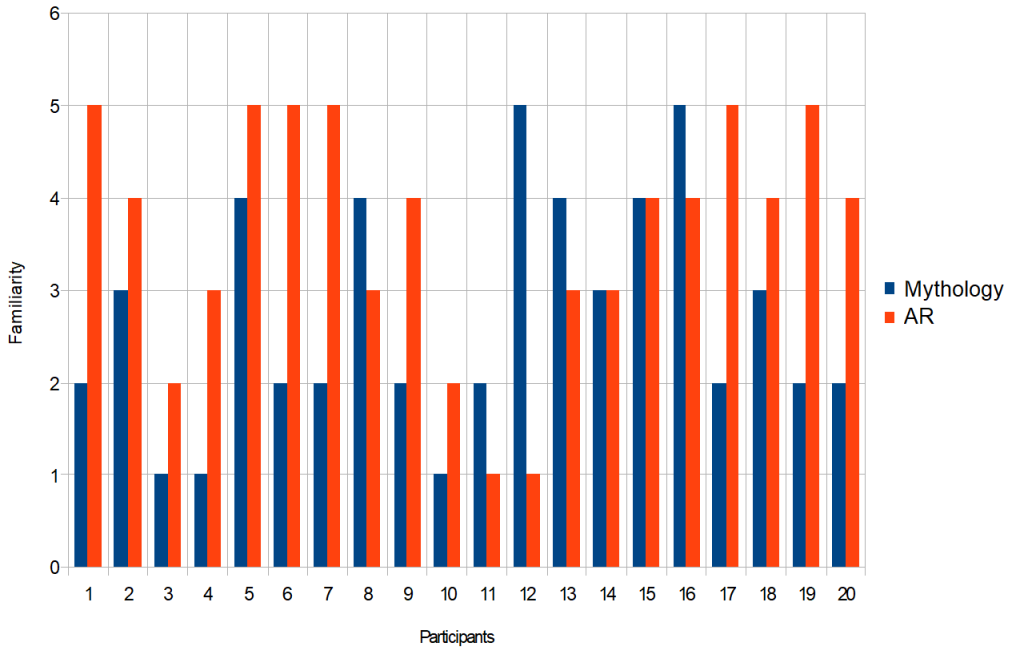


Figure 6.2.: Familiarity with Greek & Roman Mythology and Augmented Reality

6.2. Questions about the Application

6.2.1. AR Usage

Here the question was whether Augmented Reality was well used as a tool.
With 4.15 points most of them agree. However, there were also comments that especially for the Laokoon station, features would have been possible without AR.
For example, the puzzle mode to show that the statue consists of several pieces could also be completely implemented in virtual reality. Then this feature would be easier to use.

This might be true, but both the museum staff and we think that this will loosen up the connection to the statues and the museum.
Another reason against this idea would be that the presence of users in the museum would no longer be that important to use virtual reality features.

6.2.2. Comparison to Museum provided Information/ Means

With 4.7 points on the Likert scale the participants were very much in agreement.
The application provides more information than the museum itself, excluding the guided tours.
Apart from special exhibitions, there is almost no information on statues to be seen at the cast museum Munich. If you're lucky you'll find some information brochures at the entrance, but this wasn't the case during the two-week test period. Therefore the result in this case was very clear.
However, it should be added that the museum often displays information boards on special exhibitions which contain the most important information. Such an information board would probably have had a strong influence on the result.
When asked whether the app could replace a professional guide, the result was not as positive. With an average of 2.3 points the participants tend to disagree with that statement.
Which is understandable, as a proper guided tour can respond much better to the individual questions and perhaps even reveal current research results on the various statues.

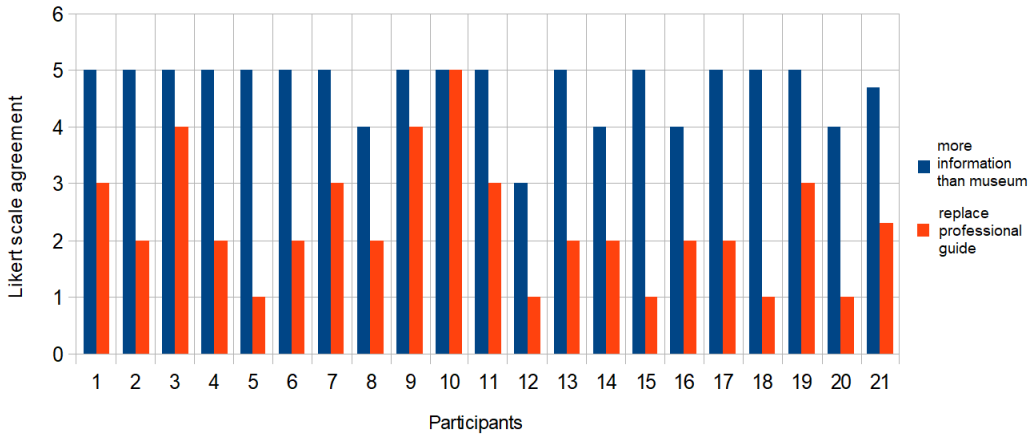


Figure 6.3.: Comparison to Museum provided Information

A little further down in the questionnaire it was asked if the Laokoon station had given an insight into the composition of the statue which would not have been possible without AR. An average of 4.15 points shows that the testers agree with this statement. Most of all, it

would have been difficult to show the composition of the individual parts of the Laokoon group with the normal resources of the museum. The original casts are usually not accessible to the public at all. And it seems even more absurd to disassemble and reassemble the statue in front of an audience.

6.2.3. Intuitiveness and Information Quality

With an average of 3.65 points the participants find the application pretty intuitive. The reason for this not quite so high value is probably the manual changing of the target statue in AR mode. How this can be fixed in the future is explained in the chapter *Future Work*.
However, the clarity of the information did not suffer from this and with an average of 4.3 points the participants find the information very descriptive.
A large part of the good evaluation probably comes from the multi-level information system. So the visitors can read short information texts to the statues and in case they are more interested the app helps to find further information on the internet.

6.2.4. Station Evaluation

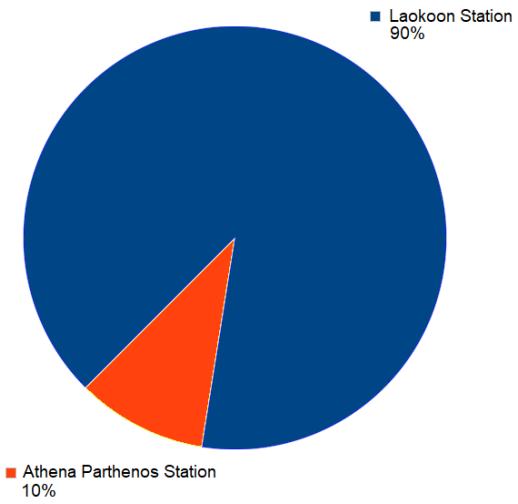


Figure 6.4.: Station Popularity Chart

Here we asked the participants which of the stations they liked best. In total there were 18 votes for the Laokoon station, 2 votes for the Athena Parthenos station and 0 votes for the remaining stations.
That the Laokoon station would please the most was expected, because most of the working time went into this station. It was also the only highly interactive station where participants didn't just read information or pressed buttons.
At the Athena Parthenos station the tracking worked very well like it did at the Laokoon

station, so this station probably got the 2 votes because it was easier to handle and less interactive.
That the other stations didn't get any votes at all was a little surprising but not completely incomprehensible. Since the tracking at the Nike station and the Aphaia station only worked very badly and the Crouching Aphrodite statue was not accessible anymore, the votes are kind of justified.
This further reinforces our view that stable tracking is one of the most important things in AR applications. The exhibition at the National Museum of Singapore had similar problems. Most of the reviews on the app in the online store are negative because the tracking was difficult and unreliable.

6.2.5. Feature Evaluation

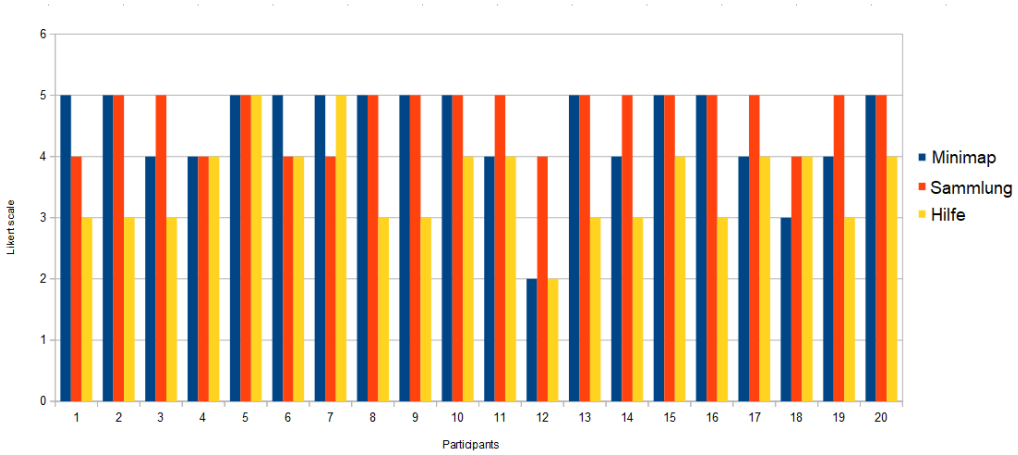


Figure 6.5.: Feature Likert Scale Results

With an average of 4.45 points the participants agree that the minimap helped them to find their way around the museum and to find certain statues more quickly.
It was no surprise that the minimap was well received. Statues look very similar for the untrained eye. Many of the statues only have a small name plate to identify them.
The minimap shows the visitor exactly where the statue is located and therefore even first-time visitors can quickly find different statues and navigate well through the museum.

The statue collection feature was even better received with an average of 4.7 points.
Participants strongly agree that this feature helped them a lot to find information about certain statues.
This good result is probably due to the close connection to the minimap. If you choose a statue in the statue collection, you can see directly after the short information text on the minimap where this statue can be found.

The lowest rated feature is the help screen with an average of 3.55 points. Nevertheless, the participants find that the help screen has given them enough information about the museum. The rather low score lets you explain that the help is not a very exciting feature and is usually only viewed once.

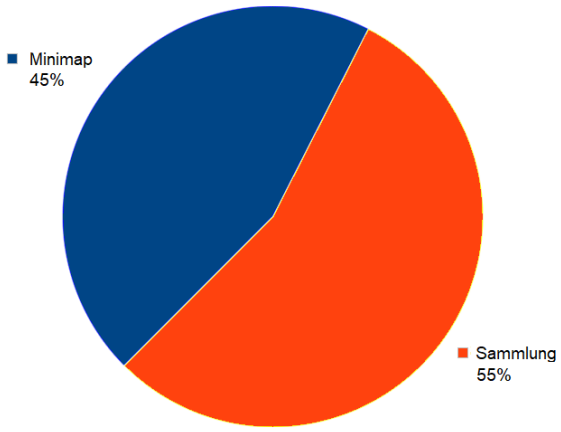


Figure 6.6.: Feature Popularity Chart

Finally we asked which feature the participants liked best. In total there were 11 votes for the statue collection, 9 votes for the minimap and 0 votes for the help screen.
The minimap and the statue collection are very closely connected in the application, and the votes of the participants reflect this.

6.3. Comparison to Classic Information Media (Texts, Images, Audioguides)

In this section of the questionnaire, specific questions were asked in order to compare classical means of museums, i.e. texts, images and audio guides, with the use of augmented reality (AR).

6.3.1. Motivation

With an average of 4.2 points the participants agree that the use of AR motivated them to study the exhibits more closely. Classic means like texts may have gained the reputation of being boring through our educational system or smartphones and tablets are simply more exciting in themselves.
In any case, the use of AR seems to have a positive effect on the motivation of the participants.

6.3.2. Interaction

On average, 4.45 points were scored for the question whether the use of AR would enable a more individual and active interaction with the exhibit. And this also seems to be one of AR's strengths. One can try to let the museum visitor actively work with the statue without endangering the statue itself. In addition, museums enjoy almost unlimited freedom in communicating information if they are using AR in combination with 3D engines like Unity. The options here are virtually limited only by one's own creativity.

6.3.3. Information Quality

The participants are not that unanimous on the question of whether information has been communicated more clearly and memorably using AR. Nevertheless, with an average of 3.75 points they tend in a positive direction. Here probably the kind of information plays a big role. Hence, the participants will surely not forget that the Laokoon group consists of several parts but in order to convey the story behind Laokoon more memorably than just text, movie-like animations would probably be necessary.

6.4. User Ideas/ Comments to improve the Application

Here the participants could make comments about things they were not particularly pleased with. Many of the things listed here like tracking problems and the manual switching of the tracked statues are covered in the chapter *Future Work*.
But there were very interesting comments on more universal problems as well.
For example, some participants had trouble pointing the tablet at the statue and operating the tablet at the same time. Another problem was that the camera must not be covered by the holding hand, which can be really difficult when the tablet is held horizontally. Therefore it would be better in the future to design the application in a way that the tablet can be held vertically. Or the tablet is not actively operated in horizontal mode while using augmented reality.
Other comments concerned the minimap. Some participants would have liked a more precise map. At the moment the minimap is only a large collection of standard Unity plane-objects. With the help of the museum we could generate a 3D model of the museum or integrate floor plan textures instead.

6.5. INTUI, Intuivive Interaction

The INTUI questionnaire is a standardized test that attempts to measure the intuitiveness of an application. It divides intuition into four factors: Effortlessness, Verbalizability, Good Feeling and Magical Experience. A global intuitivity factor is also considered.
In total, the test consists of 16 questions on the above categories and one additional question related to general intuition.
Each question is designed as a semantic differential that can score between 1 and 7 points.[19][20]

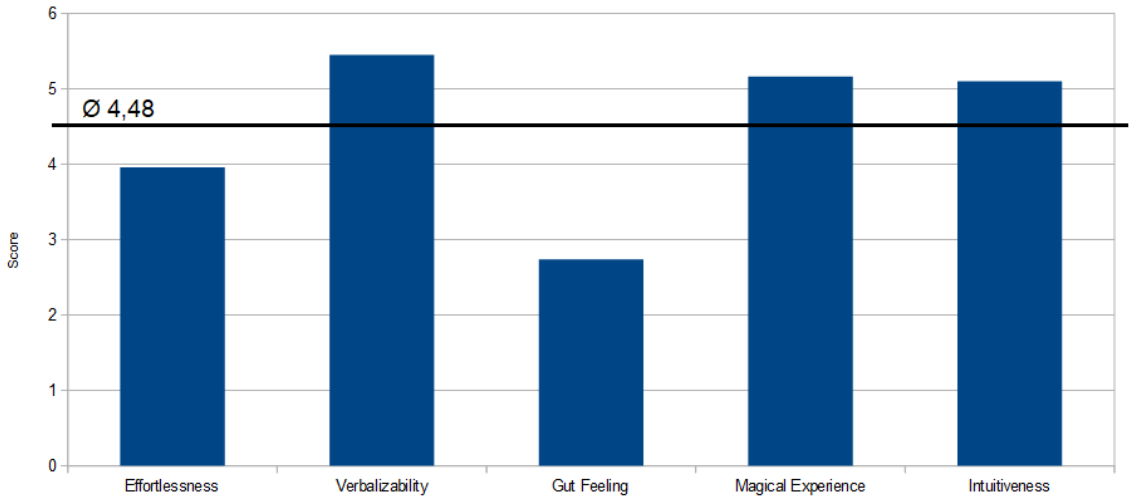


Figure 6.7.: INTUI Results, min: 1, max: 7

Effortlessness achieved an average score of 3.96 points. This circumstance can probably be explained by the fact that the users had to change the statue tracking manually. Another reason could be that it was relatively difficult to aim at the statues, hold the tablet, and not cover the camera with a hand at the same time. The section *User Ideas/ Comments* describes this problem as well.
Verbalizability achieved the highest score with 5.45 points. The relatively clear and simple structure of the application probably contributed to this result.
The lowest score with an average of only 2.74 points was achieved in the category *Gut Feeling*. This is probably because the application is trying to teach the user. For this the user has to visit different statues independently and complete the corresponding texts and stations. A pure entertainment application would likely have a higher score in this category.
With 5.16 points, the category *Magical Experience* has a respectable value and the general intuitiveness question scored an average of 5.1 points.
This gives the application an overall score of 4.48 points. This number can be used in the future to compare intuitiveness factors of different projects.

6.6. MMGS, Multimedia Guide Scale

The Multimedia Guide Scale consists of three components. The components are *General Usability*, *Quality of Interaction* and *Learnability and Control*.[21]
The component *General Usability* was too generic for us and therefore we preferred to come up with application specific questions ourselves.

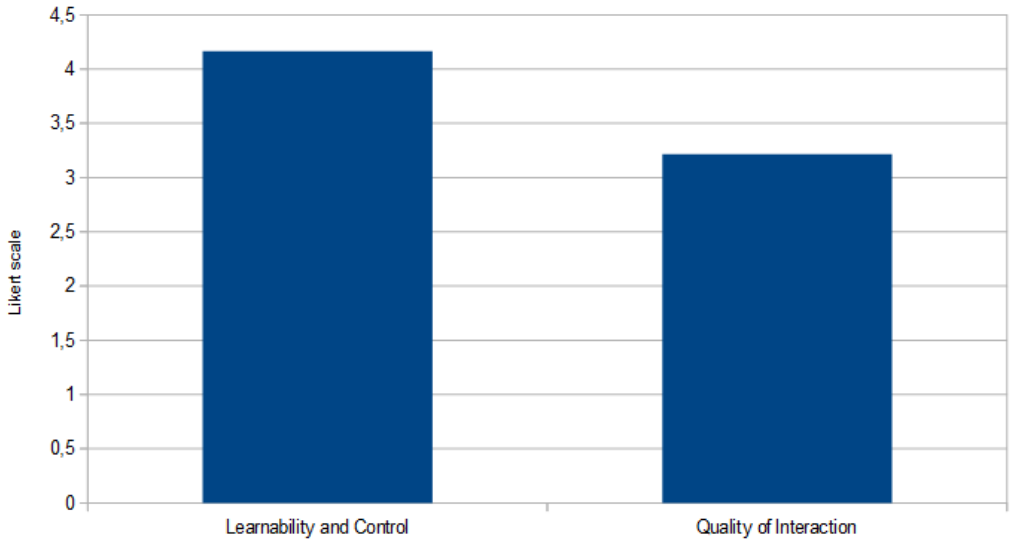


Figure 6.8.: MMGS Results, min: 1, max: 5

The component *Learnability and Control* scored an average of 4.17 points. This seems to indicate that despite various difficulties with operation, the application was not unbearably difficult to handle. However, the average score of 3.22 for the *Quality of Interaction* component suffered as a result. How this can be improved is further explained in the chapter Future Works.

6.7. Educational Effect

At the end of the questionnaire the participants were asked some questions to check if they had learnt something after using the app.
The first question was about which animal attacked Laokoon and his sons. Every participant knew it was a snake. Admittedly this was a very simple question and one could have known the answer by simply looking at the statue.
To answer the second question, however, it was not enough to just look at the statue. Here we asked which trick Laokoon was the only man to see through. Here the correct answer was that Laokoon could see through the trick of the Trojan horse. After all, 70% of all participants had answered this question correctly. The second most popular answer was that Laokoon saw through the trick of a Greek god. Nice try.
The third question was about which of the two persons depicted next to Laokoon is his younger son. Also here the participants had to investigate the statue thoroughly in order to know the correct answer and 60% managed to do so.
The fourth question related specifically to the composition of the Laokoon group. 60% of all participants knew that it consisted of 8 parts. The trick with this question was that in the puzzle mode only 7 objects showed up. In order to answer the question correctly, you had to read the information text with the younger son. Here it was mentioned that this piece actually consists of 2 parts. In development it was not possible to generate separate 3D models for those 2 pieces, because the second piece was just a relatively small fragment.
The fifth question was similar to the fourth, but a little harder. It was asked on how many parts of the statue, the body of Laokoon was divided. To answer this question correctly one had to have a good look at the individual parts of the statue. Nevertheless, 50% of the participants knew that parts of Laokoon's body were divided onto 4 parts of the statue.
The last question concerned the Athena Parthenos station. Here was asked which parts of the statue had been reconstructed. Only 45% of the participants could remember that the right arm, the left arm, the shield and the headdress had been reconstructed. However, many participants had answered parts of the question correctly and had forgotten only a few reconstructed parts.

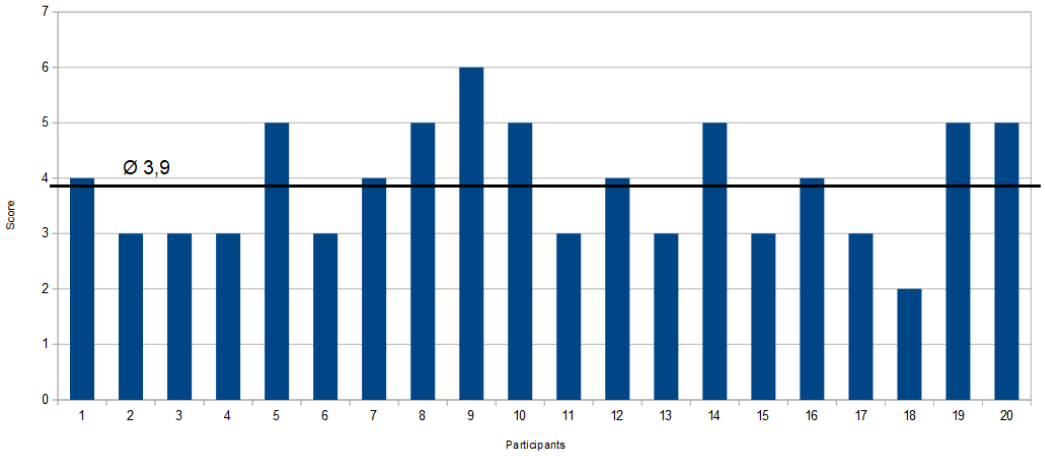


Figure 6.9.: Scores Achieved from 6 Possible Points

In the end the participants achieved an average score of 3.9 out of 6 points.
This is a good result considering that with 2.7 points on the Likert scale the participants showed rather less interest in Greek and Roman mythology. In addition, the questions at the end were difficult to get right, because they were asked in a tricky way.

7. Future Work

7.1. AR Tracking

In the subsequent lifetime of the app, some things could be added or improved. Since the museum itself has a professional 3D scanner, very precise and high resolution scans of the statues could be used for the augmented reality tracking algorithms.
In most cases a self-made scan by photogrammetry is sufficient but sometimes the tracking results are very bad.
The Athena Parthenos station works best tracking-wise because it has a very accurate 3D model of the statue that could probably not be achieved with the standard photogrammetry approaches.
Another way to solve the not perfect tracking would be to use 3D models of artists. In some cases the work of a good 3D artist can be a better approximation than the models one can generate with photogrammetry.
This is however only a real option if such a model already exists but since the 3D printer market is making great progress, in the future more and more models of even not that well known and researched statues can likely be found on the Internet.
If you take the Laokoon group as an example, it is very easy to find a very accurate 3D model.
Nevertheless, high resolution models of professional scanners are still the best option.

7.2. 3D Print Sales

Especially casting museums could greatly benefit from scanning their statues. There is certainly a market for 3D printed statues that you can buy right after the museum visit and take home with you as a memory and decoration.
Online prints of statues are already being sold today and these can usually not claim to be accurate replicas of the original.
As part of the master thesis in the case of the Laokoon group we tried to print the statue in its individual parts at the request of the museum.
Some museum employees wanted to have the statue in 7 parts to reassemble the statue.
At the moment another thesis is working on how to print connecting pieces of statues so that they can be assembled and disassembled without breaking all the time.
Maybe in the future you will be able to buy a connectable version of the Laokoon group.

7.3. Further Development

Since this master thesis will also serve as a foundation for further theses, the number of available stations will certainly increase in the future. Dozens of new statues could become part of this app.
One problems that will have to be solved in the future is surely the manual change of the target statue. Right now Vuforia does not support multiple 3D targets as it does with 2D markers, where hundreds of markers can be tracked simultaneously.
One option to solve this could be the tracking of the person inside of the building and switch the tracked statue automatically if the user is close to a certain object.
Our attempts to solve this with GPS were not very successful, because in the museum building itself, if at all, only insufficiently accurate GPS signals were received.
Another possibility would be some form of Wifi-tracking. If the museum itself had enough routers, you could locate the museum guests by triangulation.
Other ideas include various SLAM algorithms [22]. These could easily be accurate enough for the tracking of users in the museum but the implementation would be rather complex.

8. Conclusion

All in all, we've learned a lot. Museums report increasing numbers of visitors if they constantly try to create something new. Special exhibitions and events seem to work best here.
Photogrammetry programs are getting better and better, as are the 3D tracking capabilities of augmented reality frameworks. These can work together, but success is not guaranteed yet.
Modern smartphones are very good at being able to display 3D models with good framerates if the models have reduced polygon numbers. With the help of external programs it is possible to hide the reduced resolution of the processed models very well. Interactive functions like own exhibit collections, which can be brought home by visitors, seem to be especially well received in museum apps.
The use of augmented reality has its advantages and disadvantages. Advantages are the boundless freedom that creators of such apps enjoy to communicate their knowledge in a very creative way.
Disadvantages are the not yet perfect tracking algorithms and the underdeveloped technical affinity of especially older museum guests.
We have shown that with augmented reality you can show things that would otherwise be impossible with the traditional means of a museum. And that the new way of showing things gives a significant boost to motivation and with that education, especially for younger visitors.
We have also learned that there can be too many augmented reality functions and that they can be challenging even for technically affine users. In the future, with further technical innovations and people integrating technology more and more into their everyday lives, this will probably become less and less of a problem.
With such augmented reality applications, museums have an easy way to distinguish their exhibitions from those of other museums. And they should at least try to develop one, because they get easier and easier to make as time goes on.
We are excited about what will evolve from this project in the future and hope that this app or an extension of it will be used in the special exhibition of the cast museum Munich.

A. General Addenda

A.1. Laokoon information that were used in the app (German)

All information from the catalogue of the Laokoon exhibition in Berlin.[17]

A.1.1. Laokoon Torso

Laokoon war in der griechischen und römischen Mythologie ein trojanischer Priester des Apollon oder des Poseidon. Laut griechischen Autoren war Laokoon der einzige Trojaner, der den Trick des Trojanischen Pferdes der Griechen durchschaute. Er warf einen Speer auf das hölzerne Pferd, dieser prallte jedoch ab. Daraufhin erschienen zwei von Athene geschickte Schlangen, die Laokoon und seine beiden Söhne töteten.

A.1.2. Jüngerer Sohn

Der zweite große Block bildet den zweifelsohne kompliziertesten und in seiner Form auf überraschendsten Bestandteil des Statuen-Puzzels. Für das Zusammenfügen der verschiedenen Statuenteile ist er von zentraler Scharnierfunktion und veranschaulicht zugleich eindrücklich, wie anspruchsvoll das Zusammensetzen der Einzelteile angelegt war.

A.1.3. Älterer Sohn

Der dritte Block ist von hochrechteckiger Form und misst etwa 1,24m x 0,55m sowie 0,48m in der Tiefe. Die Figur des Sohnes steht auf einer merkwürdigen angeschrägten und von allen Seiten roh behauenen Plinthe hier wird eine sekundäre Beschädigung der einstigen Standfläche greifbar.

A.1.4. Altar

Ob dieser Block zudem antiken Bestand der Statuengruppe gehört oder erst nach ihrer Wiederauffindung 1506 als Ersatz für einen verlorenen Sitzblock gearbeitet wurde, ist in der Forschung umstritten. Beobachtungen vor allem zur technischen Herrichtung lassen uns die Zugehörigkeit des Blockes zu dem antiken Bestand annehmen.

A.1.5. Fuß des Laokoon

Dieses Teil bildet das Pendant zum Laokoon-Torso, bei dem das linke Bein nur bis zur oberen Hälfte des Unterschenkels erhalten ist. Der Fuß tritt lediglich mit drei Zehen auf dem Boden

auf, in der Ferse ist er stark erhoben. Unter den Zehen befindet sich eine kleine, rechteckige Scheibe von ca. 2,5cm Höhe.

A.1.6. Rechter Arm des Sohnes

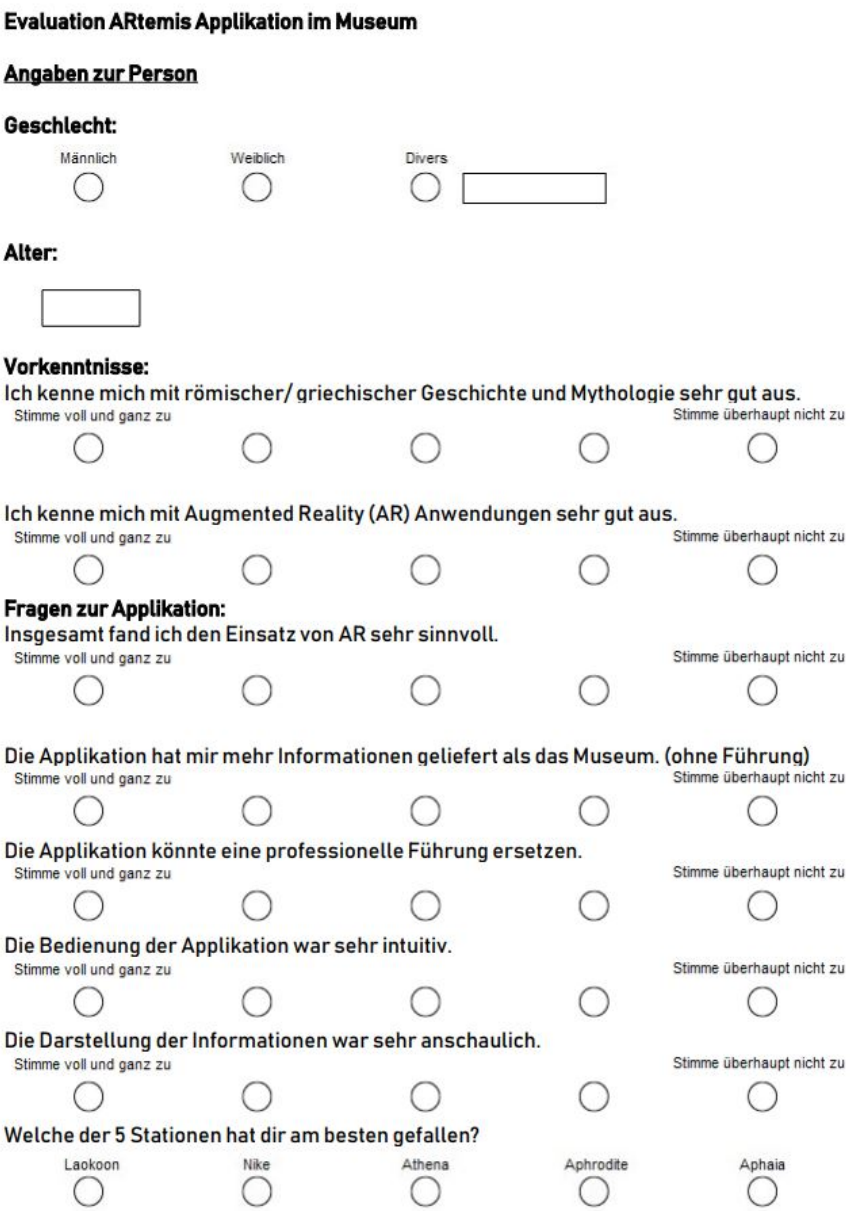
Dieses Teil ist durch einen Bruch entstanden und gehörte einst zu einem der anderen Einzelteile. Das Fragment misst etwa 0,28 x 0,23 x 0,27m. Erhalten ist ein rechter, im Ellbogen angewinkelter Arm ab der Höhe des mittleren Oberarmes, die Hand ist verloren.

A.1.7. Rechter Arm des Laokoon

Der wohl umstrittenste Teil der Statuengruppe. Als die Statuengruppe 1506 entdeckt wurde, war der Arm nicht unter den gefundenen Teilen. Giovanni Angelo Montorsoli, ein Schüler Michelangelos, wurde 1506 damit beauftragt die Statue wieder zu vervollständigen. Er ergänzte den Arm kraftvoll ausgestreckt wie er hier auch im Museum zu sehen ist. 1903, also fast 400 Jahre später, wurde der fehlende rechte Arm des Laokoon in einer Steinmetzwerkstatt gefunden.

A.2. Survey

A.3. Survey Evaluation



Evaluation ARtemis Applikation im Museum

Angaben zur Person

Geschlecht:

Männlich ○ Weiblich ○ Divers ○ [ ]

Alter:

[ ]

Vorkenntnisse:

Ich kenne mich mit römischer/ griechischer Geschichte und Mythologie sehr gut aus.

Stimme voll und ganz zu ○ ○ ○ ○ ○ Stimme überhaupt nicht zu

Ich kenne mich mit Augmented Reality (AR) Anwendungen sehr gut aus.

Stimme voll und ganz zu ○ ○ ○ ○ ○ Stimme überhaupt nicht zu

Fragen zur Applikation:

Insgesamt fand ich den Einsatz von AR sehr sinnvoll.

Stimme voll und ganz zu ○ ○ ○ ○ ○ Stimme überhaupt nicht zu

Die Applikation hat mir mehr Informationen geliefert als das Museum. (ohne Führung)

Stimme voll und ganz zu ○ ○ ○ ○ ○ Stimme überhaupt nicht zu

Die Applikation könnte eine professionelle Führung ersetzen.

Stimme voll und ganz zu ○ ○ ○ ○ ○ Stimme überhaupt nicht zu

Die Bedienung der Applikation war sehr intuitiv.

Stimme voll und ganz zu ○ ○ ○ ○ ○ Stimme überhaupt nicht zu

Die Darstellung der Informationen war sehr anschaulich.

Stimme voll und ganz zu ○ ○ ○ ○ ○ Stimme überhaupt nicht zu

Welche der 5 Stationen hat dir am besten gefallen?

Laokoon ○ Nike ○ Athena ○ Aphrodite ○ Aphaia ○

Figure A.1.: Questionnaire p. 1

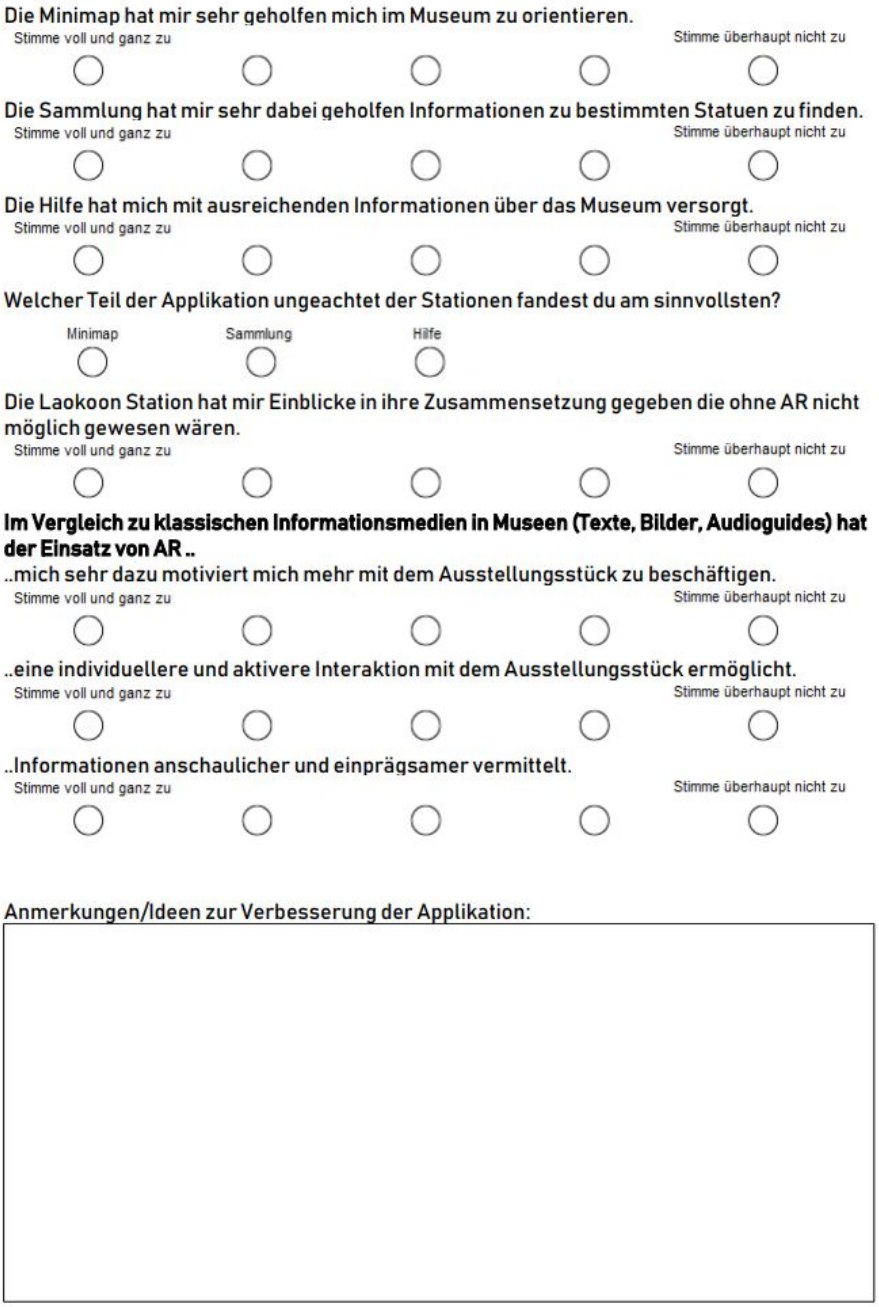


Figure A.2.: Questionnaire p. 2

INTUI Fragebogen zur Intuitivität der Bedienung (www.intuitiveinteraction.net)

Bei der Nutzung..

...handelte ich überlegt	○○○○○○○	...handelte ich spontan
...erreichte ich mein Ziel nur mit Anstrengung	○○○○○○○	... erreichte ich mein Ziel mit Leichtigkeit
...handelte ich unbewusst, ohne lange über die einzelnen Schritte nachzudenken	○○○○○○○	...führte ich bewusst einen Schritt nach dem anderen aus
...ließ ich mich von meinem Verstand leiten	○○○○○○○	...ließ ich mich von meinem Gefühl leiten
...war ich orientierungslos	○○○○○○○	...konnte ich mich gut zurechtfinden
...handelte ich ohne dabei nachzudenken	○○○○○○○	...konnte ich jeden Schritt genau begründen

Die Nutzung..

...erforderte viel Aufmerksamkeit	○○○○○○○	...ging wie von selbst
...war begeisternd	○○○○○○○	...war unbedeutend
...war einfach	○○○○○○○	...war schwierig
...war nichts Besonderes	○○○○○○○	...war ein magisches Erlebnis
...war sehr intuitiv	○○○○○○○	...war gar nicht intuitiv
...war belanglos	○○○○○○○	...war mitreißend
...fiel mir leicht	○○○○○○○	...viel mir schwer
...war faszinierend	○○○○○○○	...war trist

Im Nachhinein..

...fällt es mir schwer, die einzelnen Bedienschritte zu beschreiben	○○○○○○○	...ist es für mich kein Problem, die einzelnen Bedienschritte zu beschreiben
...kann ich mich gut an die Bedienung erinnern	○○○○○○○	...fällt es mir schwer, mich zu erinnern, wie die App bedient wird
...kann ich nicht sagen, auf welche Art und Weise ich die App bedient habe	○○○○○○○	...kann ich genau sagen, auf welche Art und Weise ich die App bedient habe

Figure A.3.: Questionnaire p. 3

MMGS Fragebogen für Multimedia Anwendungen speziell in Museen

Qualität der Interaktion

	Trifft voll und ganz zu				Trifft überhaupt nicht zu
Die App gab ein klares Feedback zu meinen Aktionen	○	○	○	○	○
Es war klar für mich, wann die App von sich aus Informationen anbietet und wann ich sie explizit anfordern muss	○	○	○	○	○
Mir war irgendwann gar nicht mehr bewusst, dass ich Bedienelemente der App benutzt habe	○	○	○	○	○

Erlernbarkeit und Kontrolle

	Trifft voll und ganz zu				Trifft überhaupt nicht zu
Ich hatte das Gefühl, die Kontrolle über die App zu haben	○	○	○	○	○
Es war leicht, die Bedienung der App zu lernen	○	○	○	○	○
Die Verwendung der App erforderte nicht viel Übung	○	○	○	○	○
Die Bedienelemente der App waren schwierig zu verstehen	○	○	○	○	○
Die App präsentierte Informationen auf verständliche Art und Weise	○	○	○	○	○
Es war schwierig, die Informationen auf dem Bildschirm zu lesen	○	○	○	○	○

Figure A.4.: Questionnaire p. 4

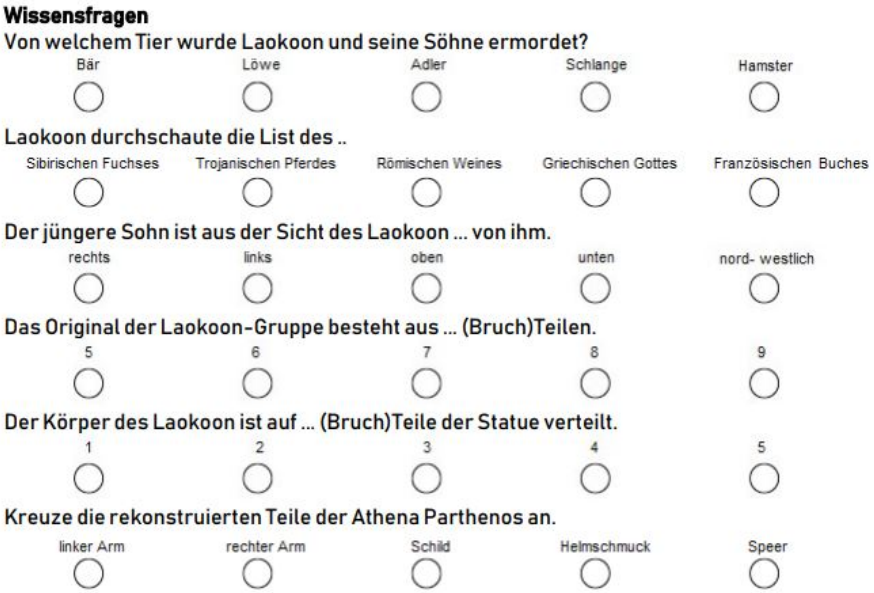


Figure A.5.: Questionnaire p. 5

																					Average
m	m	f	m	m	f	f	m	m	f	f	m	m	m	m	m	m	f	f	m		
23	24	28	21	25	22	34	41	51	50	51	62	25	24	25	22	27	26	27	25		31,65
2	3	1	1	4	2	2	4	2	1	2	5	4	3	4	5	2	3	2	2		2,7
5	4	2	3	5	5	5	3	4	2	1	1	3	3	4	4	5	4	5	4		3,6
5	5	5	4	4	5	5	5	5	5	4	3	3	2	3	4	4	5	4	3		4,15
5	5	5	5	5	5	5	4	5	5	5	3	5	4	5	4	5	5	5	4		4,7
3	2	4	2	1	2	3	2	4	5	3	1	2	2	1	2	2	1	3	1		2,3
3	4	5	3	3	3	4	4	4	5	3	1	4	4	5	3	4	4	3	4		3,65
4	4	5	4	5	5	5	5	5	5	4	2	4	4	3	4	5	4	5	4		4,3
L	L	L	AP	L	L	L	L	L	L	L	L	L	AP	L	L	L	L	L	L		
5	5	4	4	5	5	5	5	5	5	4	2	5	4	5	5	4	3	4	5		4,45
4	5	5	4	5	4	4	5	5	5	5	4	5	5	5	5	5	4	5	5		4,7
3	3	3	4	5	4	5	3	3	4	4	2	3	3	4	3	4	4	3	4		3,55
Minim	Samr	Minim	Samr	Samr	Samr	Minim	Samr	Minim	Minim	Samr	Samr	Samr	Samr	Minim	Samr	Minim	Samr	Minim	Minim	.	
5	5	4	4	5	5	4	5	5	5	5	4	2	2	3	2	5	4	5	4		4,15
5	5	4	4	3	4	4	4	5	5	4	2	4	3	5	4	5	5	4	5		4,2
5	5	4	5	5	5	5	5	5	5	5	2	3	3	4	4	5	4	5	5		4,45
5	5	4	4	4	4	4	5	5	5	4	2	2	2	1	3	4	5	4	3		3,75
Track	Manu	.	.	Teilw	Manu	.	.	.	.	Minim	Einfa	AR w	Drehe	.	.	Infobi	.	.	.	.	

Figure A.6.: Table 1, Own Questions

																					Average	
6	5	5	5	6	6	6	6	6	7	2	4	2	3	4	1	3	4	3	3	4,35	G, abs(x-7)
2	3	2	3	2	3	2	3	2	4	3	7	2	2	4	2	3	3	4	3	2,95	E, abs(x-7)
5	4	4	4	5	4	4	4	4	4	4	4	2	3	2	2	3	4	3	4	3,65	G
6	6	5	5	5	6	7	5	6	5	3	6	6	5	7	6	2	3	1	2	4,85	G, abs(x-7)
2	2	1	2	1	2	3	1	1	4	1	4	3	2	1	3	5	5	4	6	2,65	E, abs(x-7)
4	3	2	3	4	3	2	3	3	3	2	4	2	1	2	3	1	2	1	2	2,5	G
2	1	3	2	1	1	2	2	2	2	4	7	4	3	4	5	3	3	4	5	3	E, abs(x-7)
6	7	6	6	7	7	6	6	7	7	5	4	6	7	6	5	6	6	7	5	6,1	M
6	6	7	6	6	7	6	6	5	7	6	5	6	5	6	7	6	6	7	5	6,05	E
1	2	2	1	2	1	3	3	2	2	2	4	4	3	5	4	3	2	3	4	2,65	M, abs(x-7)
4	5	5	6	5	4	5	4	5	5	4	2	6	7	6	5	6	6	7	5	5,1	INT
1	1	2	1	2	2	1	1	2	2	3	5	4	4	4	4	3	2	3	4	2,55	M, abs(x-7)
5	6	6	5	6	6	6	5	6	5	6	3	7	6	7	7	3	2	4	3	5,2	E
6	7	7	6	7	7	6	6	7	6	6	4	5	5	5	5	5	4	6	5	5,75	M
2	1	2	1	2	2	2	1	1	2	2	6	2	1	2	3	1	1	2	2	1,9	V, abs(x-7)
6	7	5	6	6	6	6	6	7	7	6	5	7	6	7	7	6	7	5	6	6,2	V
2	3	3	1	2	2	2	1	2	2	2	4	2	1	3	2	1	1	1	2	1,95	V, abs(x-7)
2	2	2	3	2	3	3	3	4	3	2	1	4	4	4	3	3	3	4	2	2,85	
5	4	5	5	4	4	4	4	5	5	4	5	5	5	5	4	4	3	5	4	4,45	
2	2	1	2	2	1	1	2	2	1	3	3	1	2	3	1	4	5	4	5	2,35	
4	4	5	4	5	5	5	5	5	5	5	2	5	4	5	5	4	3	5	4	4,45	
5	5	5	5	5	5	5	5	5	5	5	3	5	5	5	5	4	3	4	4	4,65	
4	5	4	4	4	5	5	5	4	5	4	2	5	5	5	5	5	5	5	4	4,5	
1	1	2	2	1	1	2	2	2	1	2	4	2	1	2	3	2	1	2	2	1,8	abs(x-5)
5	5	4	5	4	5	5	5	4	5	4	3	4	3	4	5	5	5	4	5	4,45	
1	1	1	2	1	1	2	2	2	1	1	3	1	2	1	1	1	1	1	1	1,35	abs(x-5)
4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	20	20
2	2	2	2	4	2	2	2	2	4	2	2	4	2	4	4	2	4	2	2	14	20
1	2	2	1	1	1	1	2	1	1	2	1	1	1	2	1	2	2	1	2	12	20
7	7	7	5	8	7	8	8	8	8	5	7	8	8	8	8	7	8	8	8	12	20
3	3	2	2	4	3	3	4	4	4	3	4	3	4	3	4	4	3	4	4	10	20
2,3,4	2,3,4	3,4,5	1,2,3	2,3,4	1,2,4	3,4,5	2,3,4	2,3,4	2,3,4	2,3,4	2,3,4	1,2,3	2,3,4	1,2,3	2,3,4	1,2,3	4	1,3,4	3,4	2,3,4	9	20
4	3	3	3	5	3	4	5	6	5	3	4	3	5	3	4	3	2	5	5	3,9		

Figure A.7.: Table 2, INTUI, MMGS, Knowledge Questions

INTUI Auswertung	Effortlessness	Verbalizability	Gut Feeling	Magical Experience	Intuitiveness	
			2,65			
	4,05					
			3,65			
			2,15			
	4,35					
			2,5			
	4					
				6,1		
	6,05					
				4,35		
	0				5,1	
				4,45		
	5,2					
				5,75		
		5,1				
		6,2				
		5,05				Gesamtwertung
Average	3,9571428571	5,45	2,7375	5,1625	5,1	4,481428571

Figure A.8.: INTUI Results

MMGS Auswertung	Learnability and	Control	Quality of Interaction
			2,85
			4,45
			2,35
	4,45		
	4,65		
	4,5		
	3,2		
	4,45		
	3,75		
Average	4,1666666667		3,216666667

Figure A.9.: MMGS Results

List of Figures

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