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Master thesis

Head-mounted Augmented Reality for Outdoor Pedestrian Navigation

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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I have fully referenced the ideas and work of others, whether published or unpublished.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, 14-09.2018 Roar Gauslå Engell

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Abstract

The contribution of this thesis to the field of pedestrian navigation is twofold. First, it presents four designs for visualizing an outdoor pedestrian navigation path using Augmented Reality. Second, it incorporates these four designs in a navigation system that is evaluated by a user study in the field.

The system is developed for a Microsoft HoloLens head-mounted augmented reality device. The four visualizations are: (1) a red line on the ground; (2) a bird flying in the direction of movement; (3) colored cubes floating above the path, and (4) arrows pointing in the intended direction of movement, placed at decision points.

Twelve test persons completed the user evaluation and provided feedback in form of a questionnaire survey and short interviews. The survey evaluated the visualizations according to a series of parameters: time to complete the navigation task, a Likert-based scale of agreement with statements concerning the trustworthiness, visibility of the route and confidence in using the system, as well as the feeling of being lost during the navigation. Furthermore, a short interview about the experience was conducted. The evaluation does not result in a statistically superior design, but the subsequent interview data provides suggestions for use cases for each visualization.

Keywords: Augmented reality, head-mounted devices, Microsoft HoloLens, path visualization, outdoor pedestrian navigation, field evaluation

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1 Introduction

1.1 Creating a map on the scale of a mile to the mile

> *"That's another thing we've learned from your Nation," said Mein Herr, "map-making. But we've carried it much further than you. What do you consider the largest map that would be really useful?"*
>
> *"About six inches to the mile."*
>
> *"Only six inches!" exclaimed Mein Herr. "We very soon got to six yards to the mile. Then we tried a hundred yards to the mile. And then came the grandest idea of all! We actually made a map of the country, on the scale of a mile to the mile!"*
>
> *"Have you used it much?" I enquired.*
>
> *"It has never been spread out, yet," said Mein Herr: "the farmers objected: they said it would cover the whole country, and shut out the sunlight! So we now use the country itself, as its own map, and I assure you it does nearly as well. - Sylvie and Bruno Concluded* by Lewis Carroll (1982).

The quote above is taken from *Sylvie and Bruno Concluded,* a book written by Lewis Carroll in 1893 (Carroll, 1982). In cartographic literature the quote is used to illustrate the need for abstraction and filtering of information to be able to show the intended message on a two-dimensional map (Roth, 2009). This thesis departs from this necessity of cartography by creating a virtual three-dimensional map of scale one to one. In doing so, the goal is to develop an augmented reality navigation system for outdoor pedestrian use. In the following sections, the theoretical underpinnings of the navigation system will be outlined, before they are introduced in greater detail in chapter 2. First, the motivation and problem statement informing the thesis is described. Secondly, the specific research questions addressed

1.2 Motivation and problem statement

Arguable, the fundamental idea in cartography is retrieving and presenting information about spatial phenomena, traditionally through the medium of maps. Having maps allows the externalization of information about space and what is in it. Furthermore, having maps let users access this information without necessarily being in the space in question, that is, the information is spatial but the access to it is non-situated. Augmented reality (AR) and technologies like it are turning this practice around in what can be called situated knowledge (Roth et al., 2018). Here the premise is that the users need to be in the space they want information about. Using an AR-platform, the user can access the layers of information available at their location. This thesis is an antithesis to the approach of Cartography described above, in the sense that it does not scale down the map. A “mile to the mile” virtual map is spread out over the real world, while running no risk of blocking out the sunlight.

AR Technology, in the sense that it is a device that augments the user's perception of the physical world, has been used for centuries. Technologies like binoculars and kaleidoscopes change the perception of reality, the former to enhance perception, the latter to entertain. Modern digital augmented reality systems still aim at these goals. One promising development in AR technology allow the user to wear a head-mounted device (HMD) that display virtual objects on a screen in front of the user's eyes. In fact, digital head-mounted AR is not a new invention. Ivan Sutherland developed a head-mounted system in 1968 (Sutherland, 1968) that could display digital objects to the wearer. Only recently have such systems become widely available to the public. For this thesis a head-mounted AR device, the HoloLens, developed by Microsoft in 2016 is used. The overall motivation driving this thesis is examining the usefulness of current AR HMD technology to help pedestrian user navigate outdoors. Before AR can be used to access situated knowledge, it is necessary to develop systems that can lead the user to areas embedded with such virtual experiences. AR also exist in a context that does not take advantage of HMDs, for example smartphones. The availability of smartphones is far greater than that of HMDs, yet these are the focus of this thesis for two reasons:

First, navigating outdoor environments is a daily challenge for millions around the world when travelling to a new place. Head-mounted AR offers the potential for allowing people to navigate new spaces without hindering their interaction with the real world, since both hands are left free. Secondly, users of a head-mounted AR device can not only interact with the physical space they are in, but potentially with the augmented scene as well. This expands the possibilities for embedding space with meaningful content. Information about events or objects in space presented in the virtual scene through multimedia like videos, text etc. could potentially enhance the experience of navigating and or learning. Azuma (2016) describes current uses of AR in outdoor environments, like art installations showing the outline of the World Trade Centers over the New York skyline. Also, the New York Times (2018) developed an AR application to allow users to investigate scenes in war torn Syria from a safe distance.

The specific AR HMD used in this thesis, the Microsoft HoloLens, comes with some technological challenges; these will be described in detail in chapter 2 and addressed in chapter 3 later. Briefly, these challenges concern the positioning of the user in space since the devices come without a GNSS receiver. Another challenge is the limited Field of Vision available. This can have potential effects on the user experience outdoors, when virtual objects are large in extent or placed at great distance.

Thus, the problem statement informing this thesis is:

How can AR HMD technology be used for pedestrian navigation in an outdoor environment?

Addressing this problem is relevant in a cartographic context for several reasons. First, as mentioned above, the goal of such a navigation system is to present information about spatial phenomena, specifically the routes connecting them. Second, addressing navigation opens for questions about how to best present spatial information in the actual space it is describing. Third, with functioning AR HMD navigation systems, questions about their effect on spatial knowledge acquisition, for example learning and remembering the space a pedestrian moves through, can be investigated. In order to address the posed problem statement, a virtual outdoor world of a scale one to one is created and four different ways of navigating this virtual environment are designed and evaluated. The specific research questions posed are presented in the next section.

1.3 Research questions and objective

To address the problem statement above, the following four specific research questions will be answered by this thesis:

1. In what situations can HMD AR enhance outdoor pedestrian navigation?
2. How can a path be effectively visualized with AR?
3. Are users comfortable navigating with AR HMD technology?
4. Can the current limitations of the chosen technology be addressed effectively?

To answer these questions, a navigation system will be implemented and subsequently evaluated by conducting a user study in the field. As mentioned before, this implementation involves the development of a virtual environment to scale with the physical space. The virtual environment or scene will be conceptualized as being positioned on top of the real physical world.

Four different visualizations of the navigation path will be created within this virtual environment. They all visualize the same path; one is a red line laid out in front of the user like a carpet. Another is a red bird flying in front of the user, leading the way. The third is a series of colored cubes floating in the air above the path. Lastly, one shows directional arrows at decisions points, pointing in the intended direction of movement. The former two are continuous path visualizations, while the latter two only show the path at certain points.

To inform the discussion about the results gathered from the user study, this thesis is based on the literature on pedestrian navigation. This line of cartographic research investigates how humans navigate through both known and unknown spaces and what factors makes this easier for some while others are lost. One element within this context is how navigation systems can influence navigation performance both positively and negatively.

In the next section, the overall structure of the thesis will be presented.

1.4 Thesis structure

The thesis is divided into six chapters. Following this first chapter Introduction, the second chapter explores the state of the art within the fields of pedestrian navigation and AR. The third chapter describes the methodology applied in this thesis, specifically in the development of the navigation system and the user evaluation. Chapter four presents the results from the user evaluation. Chapter five discusses the results and provides recommendations for future work. Finally, the sixth chapter presents a conclusion.

2 Literature review and theoretical background

Augmented reality has received increased research interest the last years because of the surge of powerful devices capable of running the demanding software. The potential of such systems is not lost in the research community and calls to develop AR solutions have been made within several fields. Also, within cartography the potential of AR technology is actively being investigated. Topics like geodata visualization (Hedley, 2002), creating map visualizations in museums (Wüest, 2018) and for navigation (Rehrl, 2014), have been addressed in cartographic literature.

More recently, head-mounted AR devices like the Microsoft HoloLens have been released to the public. These devices promise to let the users interact freely with both virtual and physical environments, since their hands are left free. It is the potential of this technology for navigation that will be investigated in this thesis. Before going into the details of the navigation system designed for the thesis as well as the evaluation of it, this chapter will introduce the reader to the current literature in the fields of pedestrian navigation (chapter 2.1). Augmented reality will be defined as well as some of the technology's outdoor uses (chapter 2.2). Finally, strategies for empirically evaluating pedestrian navigation systems will be reviewed (chapter 2.3).

2.1 Pedestrian navigation

Montello (2001) separates navigation into two parts: (1) locomotion and (2) wayfinding. Locomotion is the act of physically moving through an environment, relying on sensory input. Wayfinding on the other hand involves the deliberate planning of the route outside of the immediate surroundings and involves decision making at critical points along a preplanned route. These two separate processes interact, amplify, and limit each other. In one example of this interaction Brügger et al. (2018) empirically demonstrate that when using navigation aids; "*pedestrians look at the device in expense of fixations in the direction of movement*". Brügger et al. (2018) used eye-tracking technology to analyze where users looked in the environment when navigation with and without aids. They found that the users would look less at the environment when using aids. Specifically, the egocentric directions forwards and backwards were significantly less fixed upon when walking with navigation aids. In this case the sensory input of the immediate environment is being reduced in favor of glances at the device that provides wayfinding information.

Another way of showing the relation between strategy and motion can be found in Darken and Peterson (2001). The authors discuss the navigation loop (see figure 2.1). The loop begins with a person defining a navigation goal. Then a strategy for reaching the goal is defined. The third step involves scanning the environment for clues about the progress towards to goal. This loop continues until a new goal is formed or the first is reached. The last element in figure 2.1 shows how the navigation loop is connected to the development of a cognitive map of the area. The next section (2.1.1) will go into more detail about the acquisition of spatial knowledge required to form such cognitive maps.

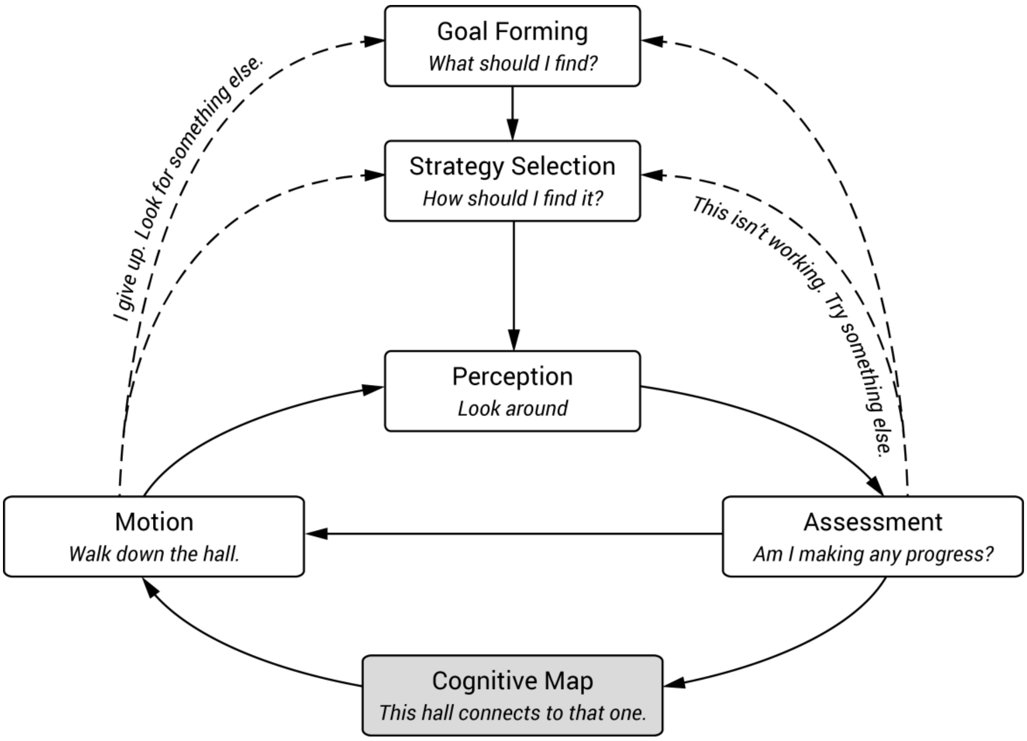


Figure 2. 1 The navigation loop. Adapted from Darken and Peterson (2001).

2.1.1 Spatial knowledge

As described in the last section, navigating in an environment creates a cognitive map to the user. Such a map is the mental representation of an area. To create such a mental map, it is necessary to acquire spatial knowledge about the area in question. There are three types of spatial knowledge identified by Siegel and White (1975) namely (1) landmark knowledge, (2) route knowledge, and (3) survey knowledge.

Landmark knowledge is the knowledge of reference points in the environment.

Route knowledge is knowledge of the geometry of the routes that connect landmarks.

Survey knowledge is the general overview that enables persons to relate route and landmark knowledge.

These types of knowledge can be acquired by different means. Either directly through first-hand experience by physically traversing the area or by looking at secondary sources likes maps or other artefacts providing information about the spatial relations of an area (Darken & Peterson 2001).

As illustrated above by the example of gaze fixation when using navigation aids, these aids can have a detrimental effect on acquiring any of these types of spatial knowledge. Several other studies have also documented the detrimental effect on spatial memory of using navigation aids. Parush et al. (2007) found that navigation with continuous and automated location of the user by GPS led to less distance traversed to reach the goal. This result speaks in favor of automated navigation systems, but as the authors state:

> *"GPS-based system can: 1. replace human perception by eliminating the need to gather information from the environment; 2. replace human cognition by eliminating the need to integrate, comprehend the information, and process it (e.g., compare it to previous information or to information in the memory); and finally, 3. eliminate the need for wayfinding decision making and problem solving."*

Parush et al. (2007) tested these statements in a virtual scenario by comparing the performance of the users navigating with full automation and users that occasionally had to actively locate themselves through quizzes. The performance of both groups was then compared without any navigation aids. This transition to unaided navigation were most detrimental to those that came from full automation, suggesting that actively engaging with the environment leads to better spatial knowledge acquisition.

In another study Huang et al. (2012) compared spatial knowledge acquisition when using different interfaces for navigation in an outdoor pedestrian context. Specifically, the interfaces mobile maps, augmented reality and voice were studied. The authors found no significant difference in the acquisition of spatial knowledge between the three tested interfaces. In fact, they discuss the effect of designing interfaces that make the navigation process easy stating: *"Only information that is 'actively' processed during the primary wayfinding activity is learnt and remembered." (Huang et al., 2012).*

Given the problems that easy navigation interfaces can have on spatial knowledge acquisition and retention, it is important to next review how navigation systems should be designed. The next section therefore reviews the literature which is important when designing navigation systems.

2.1.2 Navigation systems

In navigation studies it is largely agreed that the following four variables are important: (1) the subjects, (2) the type of navigation aid being used, (3) the timing of navigation instructions, and (4) the route taken. In the next section, these four considerations will be reviewed.

(1) When designing navigation aids for different people, their orientation capabilities and familiarity with the interface have been shown to influence usage (Mulloni, 2011). The orientation capability can be determined by self-reporting (Hegarty et al., 2002).

(2) As described above, different navigation systems can potentially have an impact on the navigation process. Rehrl et al. (2014) found that some systems lead to more pauses along the route, made the user feel uncertain and increased travel time. Specifically, they found that AR interfaces on a phone performed the worst out of the systems they tested.

(3) Giannopoulus et al (2017) found that the timing of navigation instructions influences the user performance in a navigation context. It was also found that older test persons needed directions earlier and less often than younger test participants.

(4) When designing the route several factors should be considered. Fogliaroni et al. (2018) discuss the importance of analyzing the type of intersections along the route. If a navigation study is to be replicated, the same kind of route should be used. The authors offer a way of systematically analyzing and categorizing intersections along a route, using their metric. They proposed that similar routes could be designed in other places.

When preparing to navigate through an unknown environment, it could be useful to view the route through some navigation system. Boumenir et al. (2010) found by testing different ways of preparing users to navigate through unfamiliar areas, that 2D maps outperformed detailed 3D models and AR, but direct experience was by far the best way to ensure successful navigation.

Given the diverse set of contexts that stem from the set of combinations of the four variables discussed above, designing effective navigation systems can prove a challenge. Delikostidis et al. (2016) suggest adopting a user centered approach to develop the system. They break the development process into three parts: (1) the requirement analysis, (2) production of several design solutions, and (3) evaluation of the designs. Part two and three are then iteratively performed until a solution meeting the requirements are met.

Having introduced the literature in the field of pedestrian navigation, spatial knowledge acquisition, and the important variables to consider when designing navigation systems, the next section describes AR and its potential for navigation.

2.2 Augmented Reality for Navigation

Augmented Reality is a technology that exists on a reality–virtuality continuum as proposed by Milgram et al. (1994). As visualized in figure 2.2., all technologies in this continuum are mixed reality (MR), meaning they employ virtual layers. Users can interact with the virtual layers to some extent. As the name implies, augmented reality focuses on adding information to reality, while technologies like virtual reality (VR) are at the opposite end of the spectrum, furthest from reality. VR is a technology that places the user in a completely authored virtual environment. In contrast to the comprehensive experience of VR, AR provides a virtual overlay on reality, using the real physical space to position and interact with the augmentations.

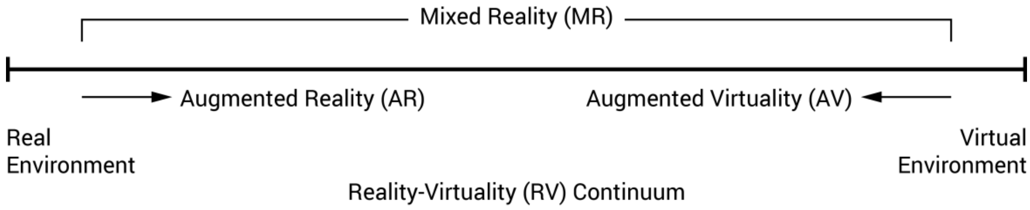


Figure 2. 2 The mixed reality spectrum by Milgram et al. (1994)

AR platforms can be divided in two categories for creating the augmentations:

(1) The platform uses a camera to show the scene; the augmentations are then added on a screen showing the real time video feed. Smart phones are an example of this technology.

(2) More AR specific platforms use headsets with a see-through screen in front of the user's eyes; the augmentations are then projected onto the screen to provide the AR effect.

As briefly mentioned in chapter one, having a functioning navigation system with AR opens for a vast array of possibilities for embedding space along the route with information or stories. As such, one major attraction of using AR for navigation purposes is the possibility for creativity when creating visualizations in three dimensions as well as the enhancement of the navigation experience with AR elements that interact with the real world. Head mounted AR leaves the user with free hands to interact with the virtual and the real world. AR technology can also combine storytelling elements from a range of other media in a unique way (Kosara, 2013). It lets the designer embed multimedia elements like video, text, sound and 3D graphics on top of reality in a way that that can strengthen the narrative being told in the actual physical space it occupies (Azuma, 2015). In addition, AR gives the user the ability to be their own cinematic director, changing perspectives at a whim. Furthermore, AR provides the potential for user interaction with the augmentations. As such, AR as a storytelling platform is positioned to employ elements of graphic design, film making, and game design, all of which are physically situated in space with the user. In the next paragraph the potentials of the intersection between storytelling, outdoor navigation and AR will be discussed further.

The Microsoft HoloLens used in this thesis belongs to the second category of AR described above. The HoloLens is one of this first completely self-contained, un-tethered, and commercially available AR HMDs (Anandapadmanaban et al., 2018). For example, it can be used without any hardware besides the glasses themselves, and the battery life of the device allows for prolonged use and free movement. The device has some limitations for outdoor use. The chapter methodology will go into the specifics of the hardware, but a few key elements will be addressed in this chapter.

First, the environmental sensors included in the HoloLens do not include a GNSS receiver, making the device non-location aware outside its immediate surroundings mapped by the camera. Second, the continuous spatial mapping performed by the device restricts its effective use in larger spatial extents. When used inside, the device is optimized to map a specific room and keep that in memory. Outside, when the environment is constantly changing, the effective use of spatial mapping for any application is reduced. Third, the area on the glasses where augmentations can be projected onto is limited, giving a small field of view (FOV). Finally, the contrast between the virtual elements projected onto the glasses and the real world is poor in daylight conditions, rendering the visualizations practically invisible during the day. The HoloLens was not designed for outdoor use. Taking it outside necessarily introduced complications, but it is possible to make adaptations to the device (Anandapadmanaban et al., 2018).

In one recent study by Anandapadmanaban et al. (2018) the authors designed a navigation system called Holo-SEXTANT for use in hazardous environments like lava terrains or for astronauts on mission. The authors have tested the system at Hawai'i Volcanoes National Park, where they had prepared a route using a DEM for height values for the placement of augmentations on the terrain at GPS. In preparation for the field test, the team made two modifications to the HoloLens. First, they cut out Visible Light Transmission (VLT) film and applied it to the HoloLens. This made the augmentations much clearer in daylight conditions, where they can be nearly impossible to see. Second, they attached a fan to the headset to cool it down, as they had experienced problems when the device was heated up in direct sunlight. Besides these modifications they used a high precision GNSS receiver to broadcast position data to the HoloLens with Bluetooth. Figure 2.3 illustrates the modifications made to the HoloLens.

Figure 2. 3 An illustration of modifications made in the Holo-SEXTANT project. Adapted from Anandapadmanaban et al. (2018).

Another key issue described in the study is related to the orientation of the virtual reality scene to the real world. Anandapadmanaban et al. (2018) developed a method to manually align the virtual route using a paper map to gauge the orientation. They found that they could follow the path with reasonable accuracy, having to stop to recalibrate occasionally. The route and the terrain they used for testing was hilly but otherwise open and thus good for GNSS signal accuracy. To visualize the path, they used a continuous line, but stressed the need for evaluating more visualizations like waypoints and directional arrows.

A study by Debandi et al. (2018) used the HoloLens in a tourism context, using AR as a means for adding location specific 3D content at locations. In their study they used image processing with the HoloLens to position the user and display relevant information. The HoloLens was connected to the internet and continuously sent images to a server that compared them to a database of known images of important buildings. When the system recognized a building, options were displayed to the user about modes of information. One of these was a 3D model of the building. Again, the user had to manually align the virtual building with the real building. During their user evaluation they found that the FOV of the HoloLens limited the view of larger augmentations, however, overall the test persons responded positively to the AR experience.

Having introduced some current experiences with the HoloLens in an outdoor environment as well as strategies for user positioning, and other challenges in this section the next section will describe the literature on evaluating navigation systems.

2.3 Evaluating navigation systems

Having reviewed the central of the many facets involved in the development of a navigation system, it is important to now review the methods by which said systems can be evaluated.

The prime inspiration on how this thesis will evaluate the navigation system is given by Rehrl et al. (2014). In their study, Rehrl et al. compared three modes of conveying route information: (1) Augmented Reality on a smartphone, (2) voice and (3) a digital map. The authors then asked the test persons to use one of these three modes to navigate along a path. The path was divided into three sub-segments and the test persons followed one mode for each segment. This within-participant study design allowed the authors to have more test persons navigating with each mode, without having to increase the total number of participants. The sequence of the modes was also varied between the users. This was done to reduce bias for one mode that could occur if, for example, every participant would follow it the same mode first. After executing the study, the results were evaluated based on three factors:

1. Effectiveness: number of stops and duration.

2. Efficiency: walking time, task completion time.

3. Satisfaction: a measure of task-load on the user.

The three modes were finally compared based on these results. They found that AR scored low on most measures, except cognitive workload, where this mode scored highest.

The next section will position the visualization system developed for this thesis in relation to the categories of navigation systems described throughout this chapter.

2.4 Positioning the thesis

The above review of the literature in the field of pedestrian navigation has outlined the dichotomies in the use and the design of navigation systems. Table 2.1 below provides an overview of these dichotomies and locates this thesis in relation to them.

As table 2.1 indicates, the design of a navigation system can be defined by how it approaches some aspects of navigation.

- The system designed for this thesis is meant for outdoor use, as it uses GPS for positioning. It is however possible to adapt the visualizations to an indoor environment.
- The system does not require the user to actively consider their route, they only need to follow the visualizations. As such, it can be classified as a passive navigation system.
- It is egocentric because the navigation instructions are given by graphic visuals in the environment. Since the visuals are on the path there are no need for mental rotations or dealing with other forms of abstraction.
- The path visualizations are adapted to pedestrian use, as discussed in chapter 3, the user must come within a certain distance of the visualization to proceed along the route. Likewise, the avatar visualization moves at a pedestrian speed.
- The mode is Augmented Reality, specifically head-mounted AR. Haptic and audio solutions could be integrated with it in the future.
- As discussed in chapter 3, the solution will be evaluated in the field.

Table 2. 1 A condensed presentation of the dichotomies described in the literature of navigation systems and an indication of how the system developed for this thesis is positioned in relation.

Dichotomies		Description
Outdoor X	Indoor	This dichotomy describes navigation systems for different environments; intersections, vertical movement and positioning etc. are treated differently.
Active	Passive X	Does the user have to actively engage with the navigation aid to position themselves and decide on the next direction to move in.
Egocentric X	Exocentric	Are navigation information provided in relation to the user like "go left", or is the spatial context provided as well (maps).
Pedestrian X	Vehicle	Is the navigation aid used by a pedestrian or in a vehicle? Systems should treat routes, environment and user differently depending on this distinction.
Mode	AR	What is the mode by which the navigation system provides information to the user; tactile, audio, map, AR etc.
Field X	Simulation	This dichotomy illustrates different strategies for evaluating the system. Is the test person placed in the physical world or navigating a virtual environment?

The next chapter will describe the process of designing, developing and evaluating the navigation system in an AR environment.

3 Methodology

This chapter describes the development of the navigation system and the strategy for evaluating it. Section 3.1 provides an overview of the research design. Section 3.2, describes the hardware used and the software implementation of the system. The last section, 3.3, discusses how the evaluation was conducted and how the collected data will be evaluated in the result chapter.

3.1 Research Design

To answer the research questions outlined in chapter 1, a twofold strategy with four subprocess was followed. First, creating path visualizations to be used with the HoloLens outdoors. Second, to evaluate if any of the visualizations performed better than the rest on some parameters. Figure 3.1 provide an overview of the subprocess involved in the development and evaluation phases.

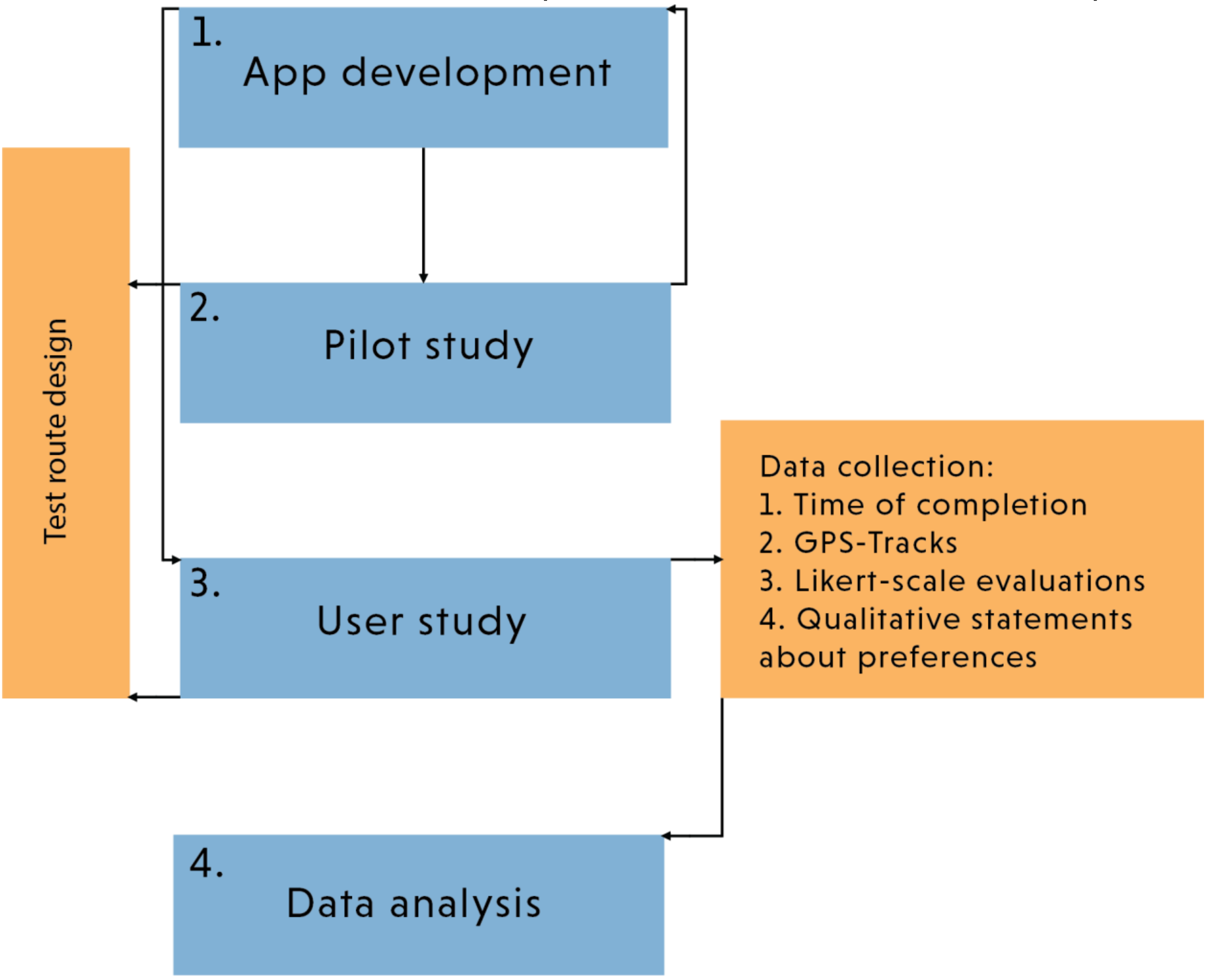


Figure 3. 1 The four phases of the thesis.

(1) The application was developed, this involved designing the route visualizations and implementing them using the frameworks introduced in the next section. (2) The first iteration of the application was tested with five participants in a pilot study. With the feedback from the pilot study, a second iteration of the application was developed. (3) The improved application was then used for the final user study. A series of data points was collected from each participant: the time taken to complete the navigation, the GPS-track, Lickert-scale answers to statements about the experience, and qualitative interview feedback. These were used for (4) the data analysis.

The next section will describe the design of the application, the hardware involved, and the software developed.

3.2 Application Design

3.2.1 Hardware

The application developed for this thesis depends on two pieces of hardware: (1) The Microsoft HoloLens and (2) a GPS enabled android smartphone. This section describes the specifics of these devices.

Table 3.1 below show the specifications of the HoloLens. The most important elements will be discussed in detail next.

CPU	Memory	Storage	Display	Input
Intel 32-bit (1GHz)	2 GB RAM 1 GB HPU RAM	64 GB (flash memory)	2.3-megapixel widescreen stereoscopic head-mounted display	Inertial measurement unit 4 sensors 1 120°×120° depth camera
Controller input	**Camera**	**Connectivity**	**Platform**	**Weight**
Gestural commands via sensors and HPU	2.4 megapixel	IEEE 802.11ac Bluetooth 4.1LE	Windows 10	579 g

Table 3. 1 The HoloLens specifications. (Microsoft, 2018)

Microsoft's HoloLens was released in 2016 for developers. The head mounted device features a pair of see through glasses. The virtual elements are projected onto part of the glasses resulting in a field of view of 30 × 17 degrees for the AR experience. The HoloLens contains an inertial measurement unit (IMU) that contains an accelerometer, gyroscope and magnetometer. The device uses a depth camera to perform spatial mapping of the environment. The spatial mapping continuously produces a 3D mesh of the environment, allowing the user to place virtual objects "on" the real world, effectively letting the virtual world interact with reality. Furthermore, the device includes Bluetooth 4.1 Low energy (LE) connectivity (Microsoft, 2018). Figure 3.2 below show the schematic of the HoloLens.

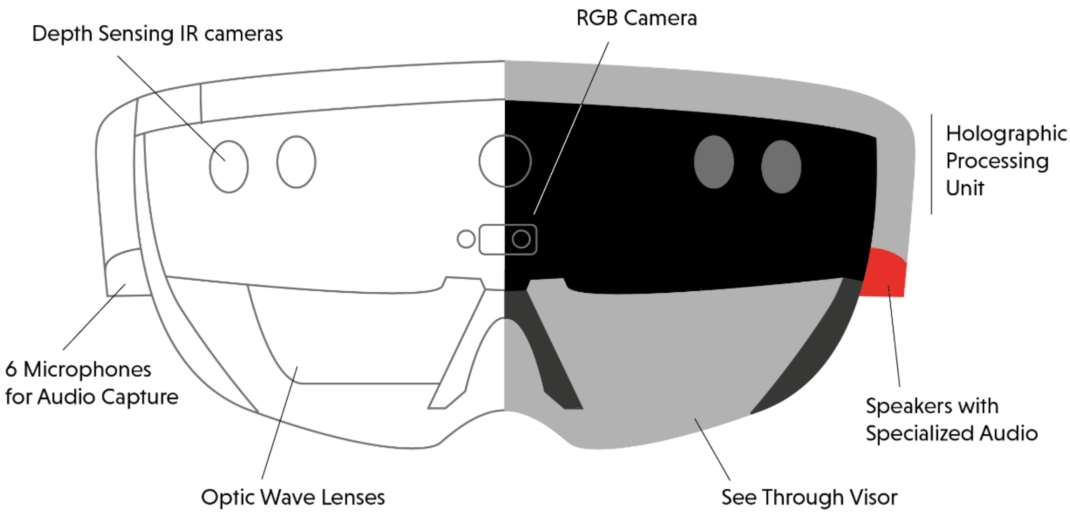


Figure 3. 2 The Microsoft HoloLens. Adopted from Anandapadmanaban et al. (2018)

The android device used to broadcast Bluetooth LE data was a HUAWEI P8 lite 2017 lite, using android version 7.0.

The next subsection will outline the software used. The external SDKs and other third-party assets as well as the specific code written for the project.

3.2.2 Software Implementation and route visualization

In the next paragraphs, the software architecture of the application will be discussed. First, an overview of the implemented route visualizations is given. Second, the different external software components will be introduced. Third, the Bluetooth connection between the GNSS aware device and the HoloLens will be explained, and lastly the design of the application itself will be described in detail.

For this thesis four different route visualizations were developed:

1. Follow floating cubes.

2. Follow directional arrows at decision points

3. Follow the line.

4. Follow an animated avatar around the route.

In general, the four visualizations can be categorized into two main groups: (1) Following floating cubes and (2) following directional arrows at decision points belong to the group; waypoint visualizations. the visualizations (3) follow the line and (4) follow an animated avatar around the route are continuous route visualizations. Waypoint visualizations show points along a route, while the continuous visualizations are shown across the entirety of the route. All four visualizations indicate the direction of movement to the user.

The line is pointing in the forward direction. The next floating cube on the route is always green while the following cubes are red. Three cubes are always visible. The directional arrows point in the direction of movement and are animated to move back and forth parallel to their direction. Lastly, the avatar faces and moves in the direction of the travel at all time.

Four visualizations were developed to represent a wide set of possible design solutions. Table 3.2 show a picture of each of the visualizations and comments on their specific design.

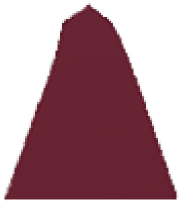
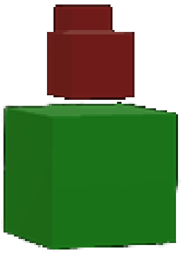
Type	Visualization	Comments
Continuous		The bird has two states: Idle and moving. The former is activated when the user is within a certain distance of the bird.
Continuous		The line visualization is drawn from the point on the route closest to the user and refreshed every few seconds.
Waypoint		The cubes float 1 meter above the ground. Three are always visible. The nearest is always green.
Waypoint		The arrow visualization shows directional arrows at decisions points. The next two arrows are always visible.

Table 3. 2 The table show the four visualizations designed for navigation.

The application was built with three frameworks: Unity, Mapbox unity SDK, and Microsoft's mixed reality SDK for Unity.

Unity is a free to use 2D and 3D game engine that provides most of the needed methods for constructing a 3D scene used for this application (Unity, 2018).

Mapbox is a company that provides maps for websites and applications as well as the functionality needed for developers to implement and use them. Mapbox has developed a software development kit (SDK) for Unity that extends Unity with the ability to add vector buildings and raster map tiles. Build into this SDK is the ability to choose the scale. At world scale, one unit of distance in Unity corresponds to one meter in the real world. This make the SDK easy to use within the game engine, making it possible to map WGS84 coordinates to game space coordinates with the same relative distances between them (Mapbox, 2018).

Microsoft´s Mixed Reality Toolkit provides the AR specific elements; the AR camera, the graphical user interface elements, and the HoloLens specific input functionality like gaze pointer and tap selection (Microsoft, 2018).

Figure 3.3 gives a detailed overview of the software developed, the external code and the code specifically written for the thesis.

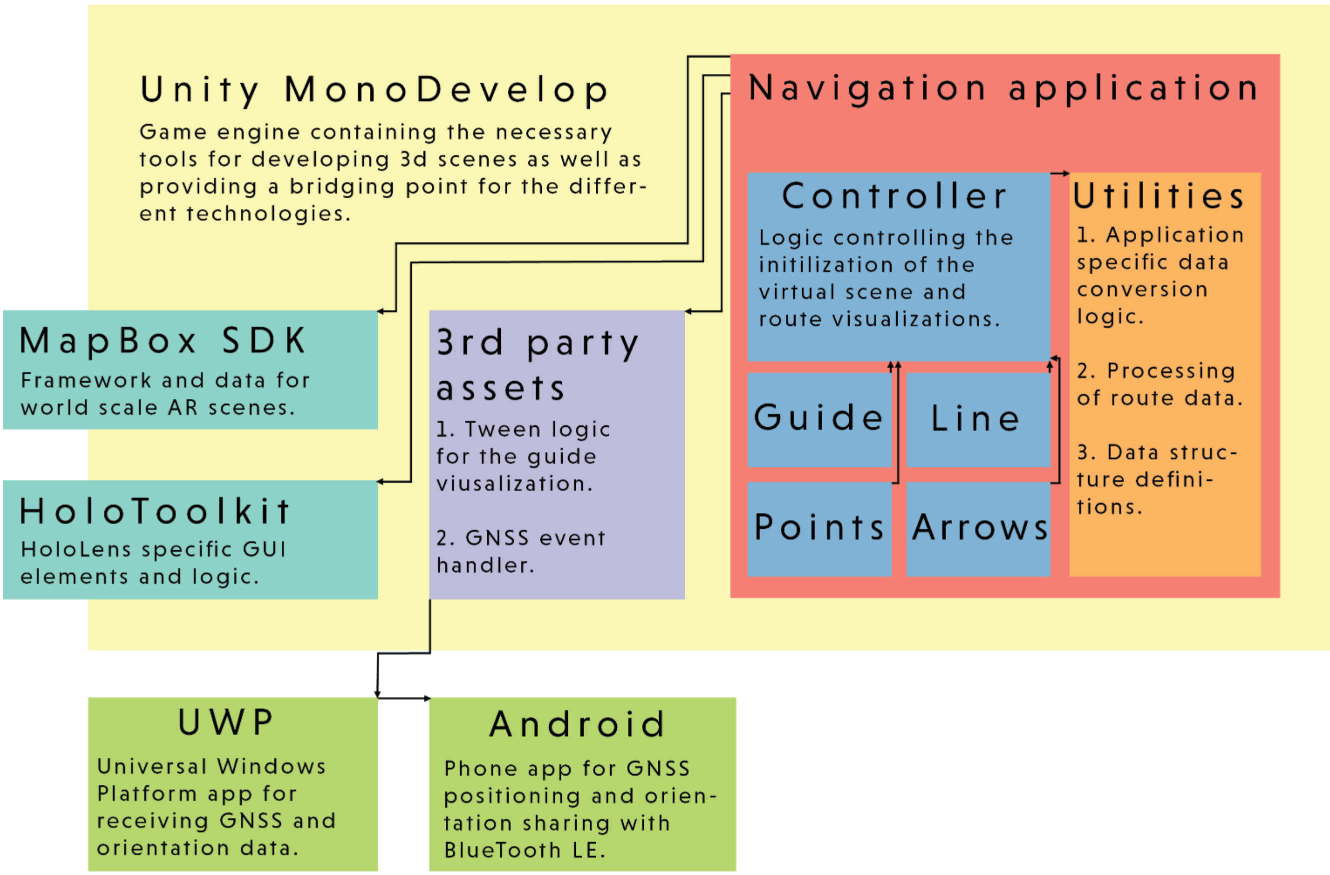


Figure 3. 3 This illustration shows the application architecture. The arrows indicate were a block is inheriting functionality and or data from.

To supply GNSS and compass data to the HoloLens a Bluetooth Low Energy advertiser was developed on a secondary android smartphone device and a receiver on the HoloLens. Bluetooth LE packets have 32 bytes free for custom data out of a total of 40 bytes per packet. To ease the data transfer, the advertisement was done using a specific Bluetooth Beacon id. The Beacon is contained as a header in the packet to allow the receiver to filter other Bluetooth signals. To advertise the data an android app was developed. The app advertises a package of twenty custom bytes containing sixteen bytes of latitude and longitude information and 4 bytes for the compass orientation. The package is refreshed several times a second to keep the compass orientation near real time on the HoloLens. The app updates the latitude and longitude information maximally once every second. To receive the information a receiver was developed on the HoloLens. This was developed with the Universal Windows Platform (UWP), which is a SDK developed by Microsoft that allows developers to work with all their products. This receiver was built within the Unity framework with bridges to HoloLens' native infrastructure.

Within the Unity application, the initial position of the user was used to set up the Mapbox AbstractMap class and retrieve the relevant tiles with data about building footprints. The AbtractMap class contains methods and properties like scale, number of tiles and geographical center. These methods are all necessary for creating the virtual world. The compass orientation was used to align the virtual world to the real world by calibrating the orientation of the game space after launching the application. To calibrate the orientation, the user had to face exactly north.

The application itself was designed to have a central controller script containing all the common functionality used by each of the visualizations, like world to game coordinate transformation and a script for 3D object spawning in the virtual scene.

A subscript was developed for each of the visualizations controlling its own private methods and specific algorithms. This design pattern was inspired by the subclass sandbox pattern described by Nystrom (2014). The pattern concentrates much of the common functionality in the controller class and leaves class specific code in the subscripts. Keeping common functionality in a single class has a list of benefits. It reduces duplicate code as every subclass inherits common methods from the controller class. This is a level of abstraction that keeps the code in the subscripts simple and hides much of the complexity. Furthermore, it allows easy expansion of similar functionality in additional subscripts. In anticipation of this potential, the private methods used within the controller class were extracted to a utility script. Abstracting the utilities like this introduces another level of abstraction but this is a tradeoff between that and code readability.

To ease parts of the development process, third party assets were used for specific functionality. Here, third party assets are different to SDKs because their scope is more specialized. The assets perform a single task while the SDK is a framework for developing. Two such assets were integrated into the project: (1) the LeanTween asset, which was used to create a continuous moving motion along the route for the avatar visualization; and (2) the GPS event handler which provides functionality to queue and parse incoming GPS data from Bluetooth.

In order to be able to change visualizations along the path dynamic it was necessary to add an interface to provide the needed functionality. For this purpose, a menu interface with check boxes was developed, allowing the user to change visualizations directly on the spot. The interface also contained a map with an indicator of the user's position and orientation. This was used to confirm that the system was located correctly. A reset button was added to the menu, to give the possibility to recalibrate the orientation and GPS location on the spot without restarting the application. Figure 3.4 shows the interface that was developed to provide calibration and visualization change functionality. The brown shapes represent the building footprints and were used to debug the orientation of the virtual world.

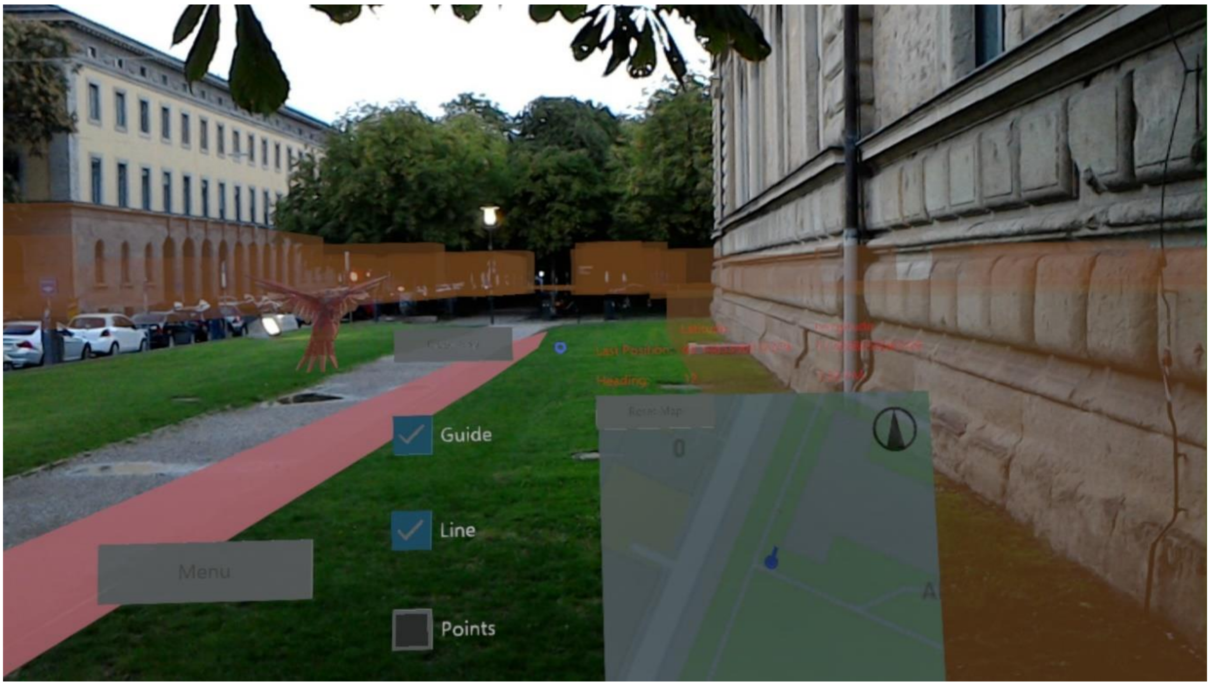


Figure 3. 4 A picture showing the interface developed to change between visualizations, ensure the correct location of the user and recalibrate the system in case it was off.

The virtual objects used two different Unity systems to register the user's progress along the route. For three visualizations (the avatar, floating cubes, and arrows) a collider was used to trigger an event, when the user got near the AR object. A collider is a Unity physics construct, which registers when *trigger* objects enter and leave their boundary (Unity3d.com, 2018). In this case, the representation of the user in the virtual scene was a trigger. For the two waypoint visualizations, the event triggered by the user getting near was to remove the reached visualization, cube or arrow and display the next. For the avatar visualization, the trigger caused the bird to fly in the direction of movement. The avatar stops moving and wait idly in case the user is out of the trigger zone. The boundary of the colliders was defined as a sphere with a diameter of 5 meters, meaning the user had to be within 5 meters to trigger the functionality.

A different approach was used for the line visualization. In this case, an algorithm would find the route point closest to the user and draw a line between that point and the subsequent three points. To avoid too much computation, this function was called once every few seconds.

In the next section the user study design will be outlined.

3.3 User study design

The following section describes the design of the user study, how the route was chosen, and the questionnaire developed for the evaluation of the route visualizations will be discussed.

Several considerations impacted the final route design. First, the route was designed to avoid traffic. The users were engaged with the task of following the navigation and it was considered unsafe for them to navigate traffic simultaneously. Second, since each user was supposed to evaluate two visualizations, the route had to be long enough for the user to get familiar with both visualizations. Last, since navigation involves making decisions about which direction to go, each part of the route had to have equally many decision points. Due to these three considerations, the route was designed to go around the Alte Pinakothek in Munich, Germany, and measured about 1000 meters. The user would follow one visualization for half of the whole route (500 meters). Each part had fourteen decision points as shown in figure 3.5.

Figure 3. 5 The test route walked by each test participant, one visualization was followed per segment.

A so called 'between subject study' was conducted over two iterations. First, a pilot study with five participants was executed. Then twelve participants performed the actual study. In both iterations one of each type of visualization (point based and continuous) was presented to the test persons, one for each segment.

Table 3. 3 The distribution of test participants between the visualizations.

All participants (N = 12)	Route segment one	Route segment two
Three participants	Avatar (bird)	Cubes
Three participants	Cubes	Avatar
Three participants	Line	Arrows
Three participants	Arrows	Line

The goal of the pilot study was to get information to tweak the route and visualizations. The task performed by the test persons was the same as in the actual user study. During the pilot study, the participants were actively questioned about features of the design for feedback, besides the feedback from the questionnaire. From the pilot study it was clear that functionality had to be added to reset the map and visualizations based on GNSS positions, as the drift coursed by slight imprecisions in the HoloLens IMU eventually lead to the virtual and real world being unaligned. Another lesson from the pilot illustrated the need for the visualizations to explicitly indicate direction of travel so to be less confusing.

In the final study, the twelve participants were divided into two groups of six based on age and experience with AR. Each participant of the same group would see the same two visualizations, but at different parts of the route. This design allowed all visualizations to be viewed six times, three times per segment of the route. This random order and division of route segment and visualization reduces learning effects that might occur if all participants saw the same visualization first and second. Table 3.3 above show how the visualizations where divided between participants.

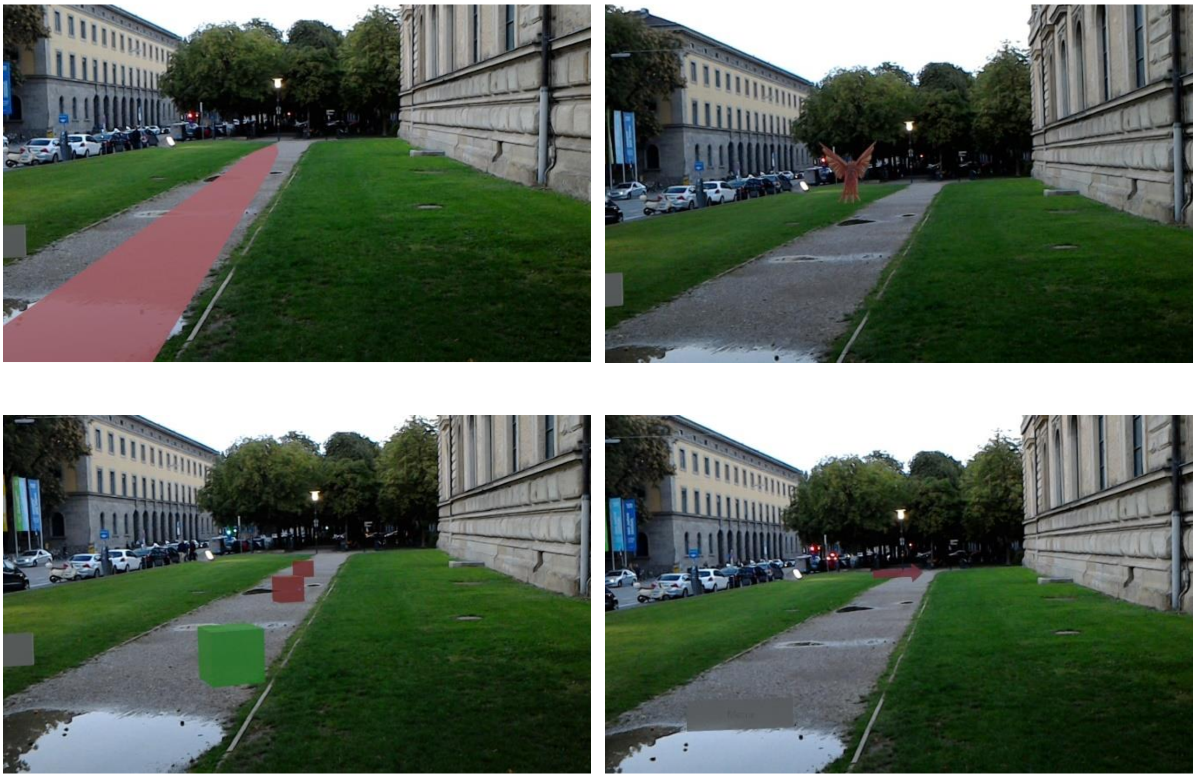


Figure 3. 6 Pictures showing the four route visualizations in the environment. Top left: red carpet on the ground. Top right: the avatar visualization, here a large red bird. Bottom left: floating cubes. Bottom right: directional arrows at decision points

The user study consisted of two parts that collected different types of data. The two parts were the actual navigation, and a questionnaire combined with a short two question interview, designed to evaluate the experience of the test person. During the navigation, every test person was asked to hold a smart phone that recorded their voice and logged their GPS position at short intervals. The questionnaire following the navigation was designed to evaluate the test persons experience with AR and their self-described navigation proficiency, with and without aids. Lastly, their experiences with the two visualizations were evaluated with four Likert scale statements by indicating level of agreement with a series of statements. These statements concerned: (1) the user's trust in the visualization; (2) their feeling of being lost; (3) their confidence about making the right turn; (4) the visibility of the visualization along the route. Following the statements, the user was prompted to imagine a use case for each of the experienced visualizations. The test persons were then asked two questions:

1. Which of the two visualizations did you prefer?

2. In what situation would you use AR for navigation?

The entire questionnaire can be found in the appendix. In the following subchapter the evaluation design of the test design is outlined.

3.3.1 User study evaluation design

Given the different nature of the collected data, it was necessary to develop a strategy for evaluating the outcome. This section will briefly discuss this strategy. The results of the study will be discussed in detail in chapter 4.

For each test person, the following data were collected:

1. Audio recordings from the "talk out loud" evaluation along the route as well as from the concluding two-question interview.

2. A GPS log of the user's actual path.

3. The Likert scale responses to statements about the experience.

4. Personal information about the test person, such as age, self-declared experience with AR, and general wayfinding ability.

With this varied information the first step while assessing the results of the study was to evaluate the GPS log data. This gave an immediate indication of the drift of the virtual scene in relation to the real world when the actual route was compared to the user's own path. The Likert-based questions was used to evaluate the experience. Finally, the open questions on the questionnaire and the interview questions were used for the thesis outlook and to get further information about potential use cases for such an application in future.

The next chapter will go through the results of the user study, starting with completion time, then moving on the Likert-scale data, and interviews. Finally, the GPS tracks are shown.

4 Results

In this chapter the performance of the visualizations in relation to the navigation process will be evaluated across the parameters outlined in the chapter 3.5. Two of the evaluation parameters are related to the test participants experiences using the system and one parameter is concerned with the stability of the system. The latter two will be treated first. In chapter 4.1, the time taken for completion will be outlined. Afterwards in chapter 4.2, the Likert-based scorings of the four visualizations are compared and a Mann–Whitney–Wilcoxon (MWW) test is performed to evaluate the trends. The interview and open questions at the end of the questionnaire will be outlined in chapter 4.3. Finally, the GPS tracks from the actual navigation will be compared to the intended route.

Twelve test participants completed the final evaluation. Of the twelve, four were female. Five were in the age group 20-25, six between 26-30, and a single participant was 31-35. Nine had completed a university level education related to GIS, geodesy or cartography. All participants indicated they used navigation aids either frequently or always when navigating to an unknown destination. All participants except one indicated they had good or excellent navigation abilities in both known and unknown locations. Seven had no or poor experience using AR technology. The user studies were performed between late August and early September. When possible, the study would take place after 19.00 to be less affected by daylight, but most studies were performed between 17.00 and 18.00 in the evening, when parts of the route were still exposed.

4.1 Navigation completion time

One of the performance parameters defined for the evaluation of the visualizations was the time to complete the navigation task. This section outlines the statistical results from this parameter, fist by the visualizations then by the participant characteristics.

The time taken to complete each of the two segments were recorded for every test person. The segments were approximately of equal length. Figure 4.1 below shows the time each segment took for each of the test participants and for each visualization. The average travel time for the total distance was 33.5 minutes with a standard deviation of 5.7. Looking at the figure, there seem to be more variance to the performance of the first segment with Test person 2 and 12 standing out with long completion times. Table 4.1 compares the average travel time for each segment. A few trends can be seen that confirm the initial impression. First, the cube and avatar visualizations performed equally well for each segment. Second, the line visualization seems to be the slowest option for both segments. Third, the arrow visualization shows the biggest difference in performance between segments, with a difference of more than 5 minutes. Looking at the average difference in completion time for each segment across all visualizations, the first segment has a variance of 5.8 minutes. Without the arrow visualization, the variance drops to 1.2 minutes. The second segment of the route has a variance of 2 minutes in completion time across all visualizations.

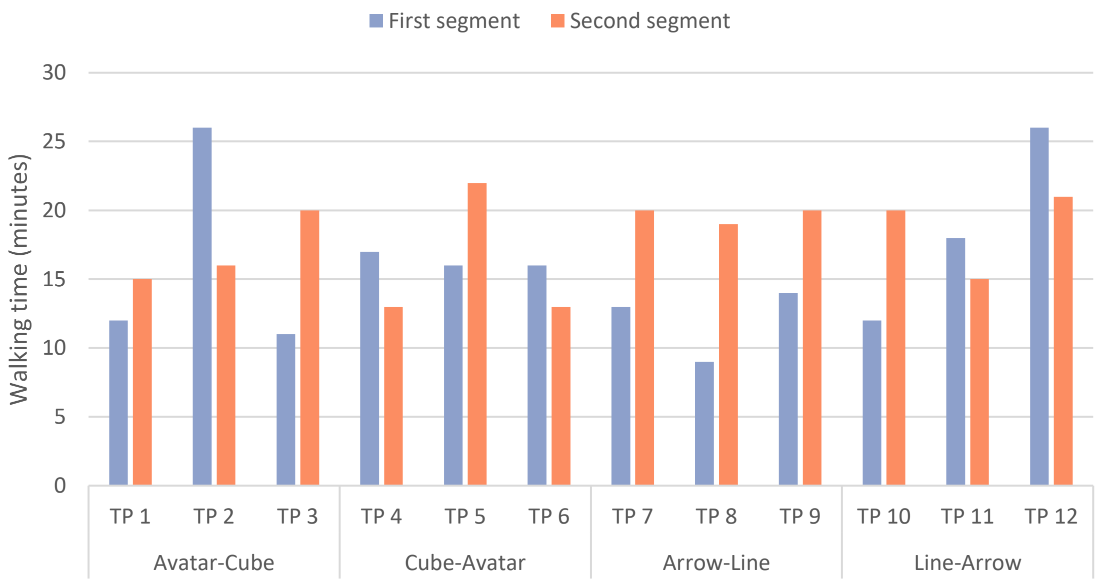


Figure 4. 1 Navigation completion time of each segment for every test participant (TP).

Visualization	First segment (min)	Second segment (min)
Cube	16.3	17
Avatar	16.3	16
Arrow	12	18.6
Line	18.6	19.6
Std.	2.4	1.4

Table 4. 1 Average navigation time for each segment by visualization.

Tables 4.2 and 4.3 show the difference between experienced and non-experienced user groups in terms of their task completion time. There are no large differences, but test persons with some experience seem to be faster in general.

Experienced	Visualization	Segment one (min)	Segment two (min)
	Avatar-Cube	11	20
	Cube-Avatar	16	13
	Arrow-Line	13	20
	Arrow-Line	9	19
	Line-Arrows	12	20
	Average (min)	12.2	18.4
	Std.	2.3	2.7

Table 4. 2 The performance of the test participants who indicated they had fair or good experience with AR

No experience	Visualization	Segment one (min)	Segment two (min)
	Avatar-Cube	12	15
	Avatar-Cube	26	16
	Cube-Avatar	17	13
	Cube-Avatar	16	22
	Arrow-Line	14	20
	Line-Arrows	18	15
	Line-Arrows	26	21
	Average (min)	18.4	17.4
	Std.	5.1	3.2

Table 4. 3 The performance of the test participants who indicated they had no or poor experience with AR

4.2 Questionnaire results

In this section the results from the questions about the user experience in the questionnaire will be reviewed. The participants were asked to answer four questions for both visualizations they followed during the navigation task. The answer to each question was a Likert-scale based indication about the level of agreement to a statement where the number 1 represents complete disagreement and 7 total agreement. Figure 4.2 summarizes the responses in a series of boxplots.

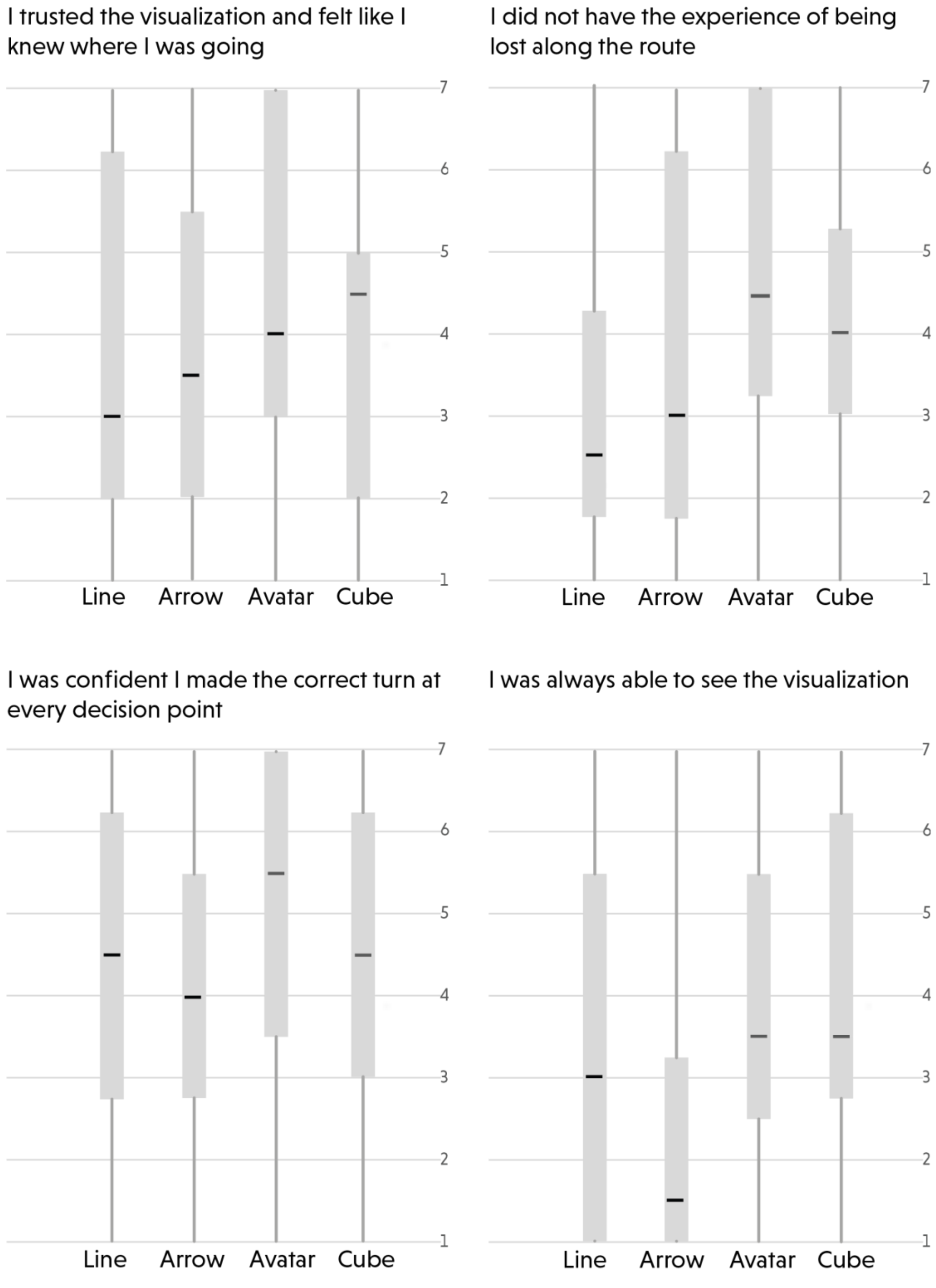


Figure 4. 2 The level of agreement with each statement, 1 meaning complete disagreement and 7 complete agreement. The black line indicates the median response. The gray box shows the 25% quartile on either side of the median.

The line visualization appears to be the least trustworthy. Similarly, it has the lowest median response to the second question, indicating that the participants had a pervasive feeling of being lost or confused about the route, when following this visualization. For confidence and visibility, the line scores similarly to the rest.

The arrow visualization scored consistently low for all questions especially for the visibility question. It also scored lowest, with a small margin, on the confidence question. The avatar visualization scored high across all questions. It was the highest scoring on confidence and not feeling lost. The cube was the most trustworthy and scored high across the rest of the parameters.

To evaluate whether any of the visualizations perform significantly different from the others across all the parameters, a MWW test is performed. This test performs a similarity evaluation by comparing the ranks of one sample group to the average ranks of both sample groups to determine if the ranks of each of the two populations are significantly different. The test assumes a total sample size from both samples to be at least 20. To reach this minimum requirement, each visualization will be evaluated against the others. For example, the confidence of the line visualization has a total of (n1) 6 responses. For the same question, the total responses for the three other visualizations are (n2) 18. The total sum of the samples thus become n1+n2 = 24. Performing the test in this manner does not give a one to one comparison but a one to many instead. A similar test was also done to see if there is a difference between continuous or waypoint type visualizations.

The null hypothesis of the test is that the two samples come from the same population.

Table 4.4 shows the p-values for each of the comparisons. The first four rows show the results from comparing each of the visualizations to the other three, for each of the four questions. The last row shows the result from comparing the continues types to the waypoint types. In no case can the null hypothesis be rejected, neither at confidence interval of 0.05 or 0.1. Meaning there are no significant differences between the samples, for both the single visualization comparison and the two groups of visualizations continuous and waypoint-based.

Table 4. 4 P-values from the Mann-Whitney-Wilcoxon test.

	Question1	Question2	Question3	Question4
Line	0.74	0.89	0.69	0.50
Arrow	0.64	0.39	0.94	0.35
Avatar	0.12	0.67	0.38	0.18
Cube	0.46	0.35	0.50	0.26
Type	0.64	0.72	0.61	0.79

In the next subchapter, the qualitative feedback gained from the user study is outlined.

4.3 Interview and qualitative responses

This section will go through the comments and responses the test participants made about the four different visualizations. This includes both the concluding interview and the written responses on the questionnaire. In the questionnaire the participants were asked about potential use situations for the visualization and during the interview, they were encouraged to explain which visualization they preferred. Based on this feedback, the results for each visualization can be summarized as follows:

1. Most test participants commented that they would either use the line visualization if they had to find a specific building or were going somewhere specific, or in combination with audio or other information to guide the user through a site, like an archeological park. One participant commented about this visualization, *"When I would need to focus on surroundings more than navigation itself".*
2. Like with the line, most comments about the arrow visualization was about using it in contexts, where navigation is secondary to some other task. One suggested using it for sports, for example indicating turns along a running route. Some indicated confusion about this visualization was*: "The arrow navigation is sometimes confusing, not sure just to walk to the arrow, or follow the direction of the arrow".*
3. The responses to the avatar or "bird" visualization were generally positive, with some comments about the problems with initially locating the visualization. Some suggest the bird should come back to get the user after some time, in case one was lost. Most participants indicated they would choose this visualization in open outdoor areas to find specific or a series of points of interest. A guide at specifically tourist sites and park navigation were common

suggestion for use. As one participant put it: *"A very effective guide - that distracts from the real world."*

4. The cube visualization was generally popular, with potential use cases mentioned spanning everything from tourist guiding, sight-seeing, point of interest finding. One participant even mentioned it had a game-like quality. There were some suggestions for improving this visualization: *"cubes could have been more like polygons"*, the test person drew a bipyramid shape with one part pointing downwards, making it clearer exactly where it was located. Another commented: *"The waypoints must convey a better idea of the general direction. One tends to trust it less when the subsequent waypoints don't align with the earlier predicted locations"*.

There were some general comments about using AR for navigation. One participant commented: *"I wouldn't use it because I'm too focused on the visualizations. It might be dangerous in traffic".* Most could see the potential for using AR for navigation and stressed the potential of using it in combination with some other media, like audio or other information visualizations. One participant who navigated with the avatar and cube visualizations commented on the differences of continuous and waypoint-based visualizations, saying: *"I'd rather use the bird because the headset isolates the user from the surroundings and the bird gives a feeling of continuity. But the box just stands."*

The next subchapter looks at the results gathered from the GPS positions of the test persons along the route.

4.4 System performance results

The navigations system's performance was evaluated by two means: (1) the GPS track for the participants during the navigation task and (2) the comments made by the users, either in the questionnaire or the concluding interview.

Figure 4.3 show the recorded GPS-tracks of the test participants around the Alte Pinakothek. The bold red line shows the actual path. Every participant started in the westernmost point of the route. The test participants were kept from walking into traffic on any of the four roads framing the area. The GPS tracks going across the streets are hence from inaccurate GPS positioning. One important result is the appearance, that some of the GPS tracks overshoot features, like turns, along the route and some seem offset. On the north side of the Alte Pinakothek, the two "humps" on the route seem to be imitated in some of the GPS-tracks. Looking at the green track, this effect is visible. The north turns in this part of the route segment is visible on the green line but seem like they far overshoot the real path and are offset on both sides. The orange track at the first west turn of the route around the south eastern corner of the Alte Pinakothek also show this overshoot. The orange track continues west straight across the field instead of turning south. In the same spot, the purple and pink tracks do appear to make the correct turn south.

Figure 4. 3 The recorded GPS tracks of the test participants along the route.

The test participant's comments about the performance of the system included mentions of the poor contrast in light conditions. Also, some mentioned the negative effect on the flow of the navigation stemming from having to repeatedly recalibrate the system.

The next chapter takes the results outlined here and put them into a context where some of the findings can be explained.

5 Discussion and recommendations for future work

In this chapter the results will be discussed in relation to the literature outlined in chapter 2. Furthermore, possible technical improvements will be suggested to avoid some of the technical issues experienced during the evaluation of this thesis.

5.1 User preferences

Even with no significantly valid results from the questionnaire results, some results can be drawn from the user study.

The arrow visualization was the only one that only marked decision points, making it the one with the farthest distance between visualizations. This point could explain some of why is received the lowest rating for visibility out of the four. The fact that it was the fastest visualization by far, for the first segment, could indicate that fewer visualizations with further between them can speed up navigation.

Users found the avatar and cube visualizations the most entertaining. The avatar because of the novelty of having a flying companion guiding you along the route. The cubes because of the game-like interaction with them.

A future evaluation of a similar system could benefit from a larger number of test participants. Also, with a better positioning system, evaluating it in real traffic situations could provide beneficial to evaluate actual use situations. Furthermore, for a second iteration of this study, multimedia elements could be embedded in the environment and the user asked to find some information along the route. This could provide additional information about how each visualization changes the user's focus and interaction with the physical and virtual worlds.

Some practical recommendations for future work can be made based on the experience gained and user feedback. First, implement a small visualization to guide the user back on track, in case they lose sight of the visualization. This could be as simple as adding a small arrow in the field of view of the user point towards the visualization, when it is out of sight. Second, optimize the contrast with augmentations and the surroundings. This is especially important when using the HoloLens outdoors. The visualizations were practically invisible in direct sunlight. Other studies have addressed this issue by applying a dark film to the glasses. The next section discusses how the nature of the visualizations changed the way users navigated at a small scale,

5.2 Visualization's effect on user track

From the interview results, it can be said that the visualizations lead to different paths taken on the same route. Following the avatar, some test persons commented that they, rather than walking straight behind the bird, would cut across corners, when they saw the bird turn ahead of them. On the other hand, the floating cube visualization let to users more strictly following the route. This finding has implications for what type of experience the designers intend to give the users. In case the route is enhanced with multimedia and geolocated information for the user, it is crucial that it is followed in a manner that brings the user near enough to trigger the events. To ensure the intended user experience, it should be considered to let the user follow a point-based visualization like the floating cubes, or potentially make the avatar slower or move closer to the user.The field of vision on the HoloLens as well as the nature of the navigation task led to test persons fixing their gaze in one direction. The implications of this are discussed in the next section.

5.3 User gaze fixation during navigation

As introduced in chapter 2, navigation systems seem to have a negative impact on user's acquisition of spatial knowledge. The literature suggests that the best way to get spatial knowledge is to actively engage with the area. For example, actively traversing an area and getting sensory input from the surroundings, will improve a person's spatial knowledge of that area. As one study suggested, walking with navigation systems as aid, will make people look forwards and backwards less often, reducing their sensory input of the area and potentially leaving them with no gain in spatial knowledge after reaching the destination. To this point, the HoloLens seemed to restrict the test person's head movement. They were fixating on the visualizations. Given the narrow field of view of the HoloLens, this was necessary to keep the visualization in sight. The next section gives recommendations for improving the positioning of the user in future work.

5.4 Positioning the virtual world

Two of the main issues in the development of the navigation app for this thesis was the localization of the user and the positioning of virtual elements in the real world. The next section will discuss how these issues can be tackled in the future.

First, locating the user was done with a smartphone and Bluetooth for this project. This approach had some limitations. The accuracy of smartphone GNSS systems is not ideal for this type of use. When navigating along a pathway, a sub-meter precision would be preferable. As discussed in the results chapter, the visualizations will appear to move into buildings or onto roads into traffic. This accuracy issues could be remedied with a high precision GNSS system with real time kinematic correction. Given the presence of trees along much of the test route, it is possible the signal could be suboptimal for much of the route due to multipathing of the signal. This solution was considered, but since the goal and purpose of using a head mounted AR system was to keep the users hands free for interaction with the real and virtual worlds, carrying a high-end GNSS receiver would defeat this purpose.

Another solution to improve the performance of the system would be to combine the IMU data from the HoloLens with GNSS positions from the smartphone to create a Kalman filter. The filter approximates the user's position based on the last position. This solution would not remove inaccuracies. It would provide a better approximation than only GNSS positions could. This solution would be possible given the constraints of this project, since it does not require extra hardware. It would, however, not solve the issues stemming for the spatial mapping done by the HoloLens itself. Given the changing environment that necessarily comes from using the systems outdoors, the juddering coming from constant spatial mapping would still occur.

To improve the spatial mapping, the ability of the HoloLens to recognize the environment without creating a new 3D mesh, a few solutions could be considered. To assist the device in recognizing the environment, physical markers could be placed in the environment along the designed route. This would allow the spatial mapping to recognize objects, like it does in an indoor environment. This solution requires the placement of physical objects on a route that is not meant to be spontaneously defined. Also, it would require the user to walk the route several times to allow the HoloLens to slowly build up its 3D mesh.

To avoid putting markers along the route, a narrow street could have been chosen for the route, rather than the open space around the Alte Pinakothek. Given the more constrained space, the HoloLens may have been able to recognize more of the environment, easing the spatial mapping. This solution could have been relevant because the application is meant to be used in urban environments too. The downsides of this approach are twofold. First, it would potentially bring the user closer to traffic, as argued earlier, using the application in traffic would not be responsible at this stage. Second, the GNSS positioning would be even less precise – suffering from the Urban Canyon problem.

The next chapter provides a conclusion to the research questions stated in the introduction.

6 Conclusion

Four research questions were posed at the beginning of this thesis. They will be answered in relation to the theory outlined and the data gathered through the user evaluation in this chapter.

The first research question asked: *In what situations can HMD AR enhance outdoor pedestrian navigation?* As described in chapter 4, there were several suggestions from the test persons about when AR could be useful. Most suggestions were related to sightseeing, where the potential to add multimedia elements along a path seemed promising to many of the test persons. Another case suggested was navigating while focused on something else. For example, when doing sports like running. In chapter 5, it was discussed how the users were fixating on the visualizations and given the narrow field of view of the HoloLens, which leads to very little head movement. As described in chapter 2, not looking in different directions during navigation can potentially reduce spatial knowledge acquisition, thus leaving people reliant of navigation technology rather than more spatially aware. At this stage of development of AR HMD, it is unclear whether it is a technology that benefits spatial learning, but it does not seem to.

The second research question asked: *How can a path be effectively visualized with AR?* This study found no statistically significant answers to this question across four parameters: (1) trust in the visualization (2) feeling of being lost (3) confidence at decision points, and (4) visibility of the visualization. This is possibly due to the size of the evaluation; a larger study could address this question further.

The third research question asked: *Are users comfortable navigating with AR HMD technology?* Most test persons were entertained by the novelty of the system, but some factors did reduce comfort. The limited field of view of the system sometimes made it hard to spot the visualizations. Also, some test persons expressed concern about using the HoloLens in traffic, especially at the current stage of the technology. They were so distracted by the visualizations, it could potentially have been dangerous to use in traffic. One interesting note to make is that no test person mentioned feeling dizzy or having blurred vision while using the HoloLens outdoors, something that is known to happen indoors.

The fourth question asked: *Can the current limitations of the chosen technology be addressed effectively?* The two biggest issues with the HoloLens are: (1) positioning the user and (2) the contrast between the AR scene and the environment. The first issues have been addressed in other studies more effectively than here, for example, by using a higher precision GPS receiver. All other studies as well as this had to develop some method for adjusting the orientation of the virtual scene to have it align with the real world. In this implementation, the user had to use the compass on a smartphone to orientate themselves exactly north to calibrate the orientation. Some automatization of this process could improve the user experience substantially. Even with correct orientation and high precision GPS data, the AR scene still has a substantial amount of drift. In current studies, this is also, like the orientation, manually adjusted and could benefit from automatization.

7 References

Anandapadmanaban, E., Tannady, J., Norheim, J., Newman, D., & Hoffman, J. (2018). Holo-SEXTANT: An augmented reality planetary EVA navigation interface. Alburquerque, NM: 48th International Conference on Environmental Systems.

Azuma, R. (2015). Location-based mixed and augmented reality storytelling. *Fundamentals of Wearable Computers and Augmented Reality*, (2), 259–276.

Azuma, R. T. (2016). The most important challenge facing augmented reality. *Presence: Teleoperators and Virtual Environments*, *25*(3), 234–238. https://doi.org/10.1162/PRES_a_00264

Boumenir, Y., Georges, F., Rebillard, G., Valentin, J., & Dresp-Langley, B. (2010). Wayfinding through an unfamiliar environment. *Perceptual and Motor Skills*, *111*(3), 829–847.

Brügger, A., Richter, K.-F., & Fabrikant, S. I. (2018). Which egocentric direction suffers from visual attention during aided wayfinding? In *Eye Tracking for Spatial Research, Proceedings of the 3rd International Workshop* (pp. 22–27). Zürich: ETH Zurich. https://doi.org/10.3929/ethz-b-000222472

Carroll, L. (1982). Sylvie and Bruno concluded. In: E. Guillaro (Ed.), The complete illustrated works of Lewis Carroll. New York, New York: Avenel Books. (Originally published in 1893).

Darken, R. P., & Peterson, B. (2014). Spatial orientation, wayfinding, and representation., *Handbook of Virtual Environment Technology*.

Debandi, F., Iacoviello, R., Messina, A., Montagnuolo, M., Manuri, F., Sanna, A., & Zappia, D. (2018). Enhancing cultural tourism by a mixed reality application for outdoor navigation and information browsing using immersive devices. In *IOP Conference Series: Materials Science and Engineering*. IOP Publishing.

Delikostidis, I., van Elzakker, C. P., & Kraak, M.-J. (2016). Overcoming challenges in developing more usable pedestrian navigation systems. *Cartography and geographic information science*, *43*(3), 189–207. https://doi.org/10.1080/15230406.2015.1031180

Fogliaroni, P., Bucher, D., Jankovic, N., & Giannopoulos, I. (2018). Intersections of our world. In S. Winter, A. Griffin, & M. Sester (Ed.), *10th International*

Conference on Geographic Information Science (Article No. 3; pp. 3:1–3:15). Schloss Dagstuhl–Leibniz-Zentrum für Informatik.

Giannopoulos, I., Jonietz, D., Raubal, M., Sarlas, G., & Stähli, L. (2017). Timing of Pedestrian Navigation Instructions. In *13th International Conference on Spatial Information Theory (COSIT 2017)* (Vol. 86, p. 16). Schloss Dagstuhl, Leibniz-Zentrum für Informatik GmbH.

Giannopoulos, I., Kiefer, P., Raubal, M., Richter, K.-F., & Thrash, T. (2014). Wayfinding decision situations: A conceptual model and evaluation. In M. Duckham, E. Pebesma, K. Stewart, & A. Frank (Ed.), *International Conference on Geographic Information Science* (pp. 221–234). Springer. https://doi.org/10.1007/978-3-319-11593-1_15

Hedley, N. R., Billinghurst, M., Postner, L., May, R., & Kato, H. (2002). Explorations in the Use of Augmented Reality for Geographic Visualization. *Presence: Teleoperators & Virtual Environments*, *11*(2), 119–133.

Hegarty, M., Richardson, A. E., Montello, D. R., Lovelace, K., & Subbiah, I. (2002). Development of a self-report measure of environmental spatial ability. *Intelligence*, *30*(5), 425–447. https://doi.org/10.1016/S0160-2896(02)00116-2

How We Created a Virtual Crime Scene to Investigate Syria's Chemical Attack - The New York Times. (2018, June 24). Retrieved from https://www.nytimes.com/interactive/2018/06/24/world/middleeast/douma-syria-chemical-attack-augmented-reality-ar-ul.html Last accessed on 14/9/2018

Huang, H., Schmidt, M., & Gartner, G. (2012). Spatial knowledge acquisition with mobile maps, augmented reality and voice in the context of GPS-based pedestrian navigation: Results from a field test. *Cartography and Geographic Information Science*, *39*(2), 107–116. https://doi.org/10.1559/15230406392107

Kosara, R., & Mackinlay, J. (2013). Storytelling: The next step for visualization. *Computer*, *46*(5), 44–50.

LeanTween. (n. d.). retrieved from http://dentedpixel.com/LeanTweenDocumentation/classes/LeanTween.html Last accessed on 14/9/2018

Mapbox (2018) Maps SDK for unity. Available at *https://www.mapbox.com/unity-sdk/maps/overview/* Last accessed on 14/9/2018.

Microsoft (2018) retrieved from https://docs.microsoft.com/en-us/windows/mixed-reality/hololens-hardware-details Last accessed on 14/9/2018

Milgram, P., Takemura, H., Utsumi, A., & Kishino, F. (1995). Augmented reality: A class of displays on the reality-virtuality continuum. In *Telemanipulator and telepresence technologies* (Vol. 2351, pp. 282–293). International Society for Optics and Photonics.

Montello, D. (2001). Spatial cognition. *International encyclopedia of the social and behavioral sciences*, 14771–14775. Oxford: Pergamon Press.

Mulloni, A., Seichter, H., & Schmalstieg, D. (2011). Handheld augmented reality indoor navigation with activity-based instructions. In *Proceedings of the 13th international conference on human computer interaction with mobile devices and services* (pp. 211–220). Stockholm, Sweden: ACM.

Nystrom, R. (2014). *Game programming patterns*. Genever Benning.

Oslebo, D. (2017, Januar 18). GPS on the Microsoft Hololens. Retrieved from https://www.gamedev.net/articles/programming/general-and-gameplay-programming/gps-on-the-microsoft-hololens-r4497

Parush, A., Ahuvia, S., & Erev, I. (2007). Degradation in spatial knowledge acquisition when using automatic navigation systems. In *International Conference on Spatial Information Theory* (pp. 238–254). Berlin, Germany; Heidelberg, Germany: Springer.

Rehrl, K., Häusler, E., Leitinger, S., & Bell, D. (2014). Pedestrian navigation with augmented reality, voice and digital map: final results from an in situ field study assessing performance and user experience. *Journal of Location Based Services*, *8*(2), 75–96. https://doi.org/doi:10.1080/17489725.2014.946975

Roth, R. E. (2009). A qualitative approach to understanding the role of geographic information uncertainty during decision making. *Cartography and Geographic Information Science*, *36*(4), 315–330.

Roth, R. E., Young, S., Nestel, C., Sack, C., Davidson, B., Janicki, J., Knoppke-Wetzel, V., Ma, F., Mead, R., Rose, C. & Zhang, G. (2018). Global Landscapes: Teaching Globalization through Responsive Mobile Map Design. The Professional Geographer, 70(3), 2018. https://doi.org/10.1080/00330124.2017.1416297

Siegel, A. W., & White, S. H. (1975). The development of spatial representations of large-scale environments. In H. Reese (Ed.), *Advances in child development and behavior* (Vol. 10, pp. 9–55). New York: Academic Press.

Sutherland, I. E. (1968). A head-mounted three dimensional display. In *Proceedings of the December 9-11, 1968, fall joint computer conference, part I* (pp. 757–764). ACM.

Unity (2018) *Unity - Manual: Unity Manual*. [online] Docs.unity3d.com. Available at: http://docs.unity3d.com/Manual/index.html Last accessed on 14/9/2018.

Unity3d.com. (2018). *Unity - Collider 2D*. [online] Available at: https://unity3d.com/learn/tutorials/topics/physics/colliders-triggers Last accessed on 14/9/2018.

Van Elzakker, C. P., Delikostidis, I., & van Oosterom, P. J. (2008). Field-based usability evaluation methodology for mobile geo-applications. *The Cartographic Journal*, *45*(2), 139–149. https://doi.org/10.1179/174327708X305139

Wüest, R., & Nebiker, S. (2018). Geospatial augmented reality for the interactive exploitation of large-scale walkable orthoimage maps in museums. In *Proceedings of the 2017 International Cartographic Conference* (Vol. 1, p. 124). Washington, D.C.

Appendix

Information

Thank you for agreeing to participate in this user study. The duration of the whole study (including filling out the questionnaire) will be approximately 30-40 minutes and you will walk one kilometer. The purpose of this study is to evaluate a navigation app I've developed as part of my master thesis. In my thesis I explore how head mounted Augmented Reality can be used for navigation and how the route visualizations themselves can play a role in the navigation experience. You will be presented with an unknown route around the Alte Pinakothek. Your task is simply to follow the route as closely as possible. After approximately 500m, you will make one stop to change the route visualization. If you agree to be voice recorded, it would also be helpful if you would "think out loud" while you walk along the route. You are free to comment whatever comes to your mind in relation to the route visualization as you proceed. When you have finished the route, I will present you a questionnaire aiming to evaluate your overall experience. Any feedback you provide will be treated anonymously. This is an exploratory exercise, so all your comments are greatly appreciated.

Questionnaire

In this first part, you will be asked to answer a few questions about yourself.

What is your age?

20-25	26-30	31-35	36-40	41-45	46-50	51-55	56-60

What field of study did you complete/currently pursue?

What is your experience with Augmented or Virtual reality?

None	Poor	Fair	Good	Excellent

How often do you use navigation systems when you visit new places?

None	Sometimes	Frequently	Always

Please rank your abilities to orient yourself and navigate with the help of a map in places that you visit for the first time.

Poor	Fair	Good	Excellent

Please rank your abilities to orient yourself and navigate with the help of a map in places that you have visited before.

Poor	Fair	Good	Excellent

Next, you will be provided with several statements. Please check the box that best fits your experience in relation to it, where 1 corresponds to **Strongly Disagree** and 7 to **Strongly Agree.**

I trusted the visualization and felt like I knew where I was going.

	1 Strongly Disagree	2	3	4	5	6	7 Strongly Agree
Visualization: 1							
Visualization: 2							

I did not have the experience of being lost along the route

	1 Strongly Disagree	2	3	4	5	6	7 Strongly Agree
Visualization: 1							
Visualization: 2							

I was confident I made the correct turn at every decision point.

	1 Strongly Disagree	2	3	4	5	6	7 Strongly Agree
Visualization: 1							
Visualization: 2							

I was always able to see the visualization.

	1 Strongly Disagree	2	3	4	5	6	7 Strongly Agree
Visualization: 1							
Visualization: 2							

Given the visualizations you just followed; in what context would you find it useful to use such a visualization for navigation? E.g. finding the nearest bakery or between historical sites.

Visualization 1:   Visualization2:

Do you have any further comments or suggestions?

Thank you for participating!