LandMarkAR: An application to study virtual route instructions and the design of 3D landmarks for indoor pedestrian navigation with a mixed reality head-mounted display

GEO 511 Master's Thesis

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Abstract

Mixed Reality (MR) interfaces on head-mounted displays (HMDs) have the potential to replace screen-based interfaces as the primary interface to the digital world. They potentially offer a more immersive and less distracting experience compared to mobile phones, allowing users to stay focused on their environment and main goals while accessing digital information. Due to their ability to gracefully embed virtual information in the environment, MR HMDs could potentially alleviate some of the issues plaguing users of mobile pedestrian navigation systems, such as distraction, diminished route recall, and reduced spatial knowledge acquisition. However, the complexity of MR technology presents significant challenges, particularly for researchers with limited programming knowledge. This thesis presents "LandMarkAR" to address those challenges. "LandMarkAR" is a HoloLens application that allows researchers to create augmented territories to study human navigation with MR interfaces, even if they have little programming knowledge. "LandMarkAR" was designed using different methods from human-centered design (HCD), such as design thinking and think-aloud testing, and was developed with Unity and the Mixed Reality Toolkit (MRTK). With "LandMarkAR", researchers can place and manipulate 3D objects as holograms in real-time, facilitating indoor navigation experiments using 3D objects that serve as turn-by-turn instructions, highlights of physical landmarks, or other information researchers may come up with. Researchers with varying technical expertise will be able to use "LandMarkAR" for MR navigation studies. They can opt to utilize the easy-to-use User Interface (UI) on the HoloLens or add custom functionality to the application directly in Unity. "LandMarkAR" empowers researchers to explore the full potential of MR interfaces in human navigation and create meaningful insights for their studies.

Keywords: Application, Augmented Reality, HoloLens, Mixed Reality, MRTK, Navigation, Unity, Wayfinding

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Abbreviations

AR	Augmented Reality
ASA	Azure Spatial Anchor
GIS	Geographic Information System
GPS	Global Positioning System
GUI	Graphical User Interface
HMD	Head-mounted Display
IMU	Inertial Measurement Unit
MR	Mixed Reality
MVC	Model View Controller
OR	Operation Room
OST	Optical See-Through
POV	Point of View
RGB	Red, Green, and Blue
SLAM	Simultaneous Localization and Mapping
VR	Virtual Reality
VST	Video See-Through
WIMP	Windows, Icons, Menus, Pointers
WLAN	Wireless Local Area Network

1   Introduction

Until the dawn of the digital age, human perception and expression have been tied to the physical world; that is, physics, natural materials, and time (Pangilinan, Lukas, and Mohan, 2019). Likewise, the consumption and communication of spatial knowledge (i.e., cartography and navigation) was tied to humans' ability to use physical materials for visual communication of (spatial) knowledge (Lewis, 1987). Moreover, their ability to perceive and interpret natural and human-made physical cues (i.e., landmarks) in the environment helped them navigate or establish new spatial knowledge (Montello, 2005).

Computers offer novel and increasingly sophisticated ways for humans to express themselves. They have continuously become more mobile, making powerful computing available wherever we go. For example, they can present current location and orientation information and contextually meaningful navigational cues on the user's request. However, computers are still restricted by their interface. Even devices with multi-touch interfaces, one of the most widely adopted interfaces to modern computers (Shneiderman et al., 2010), have a clear boundary that separates their users from the digital world. When navigating, users must mentally connect the information on the screen to physical cues in their environment.

Screen-based interfaces require the visual attention of their users. On the other hand, immersive technologies blur the boundary between the real and virtual worlds (Suh & Prophet, 2018). Immersive technologies currently rely on head-mounted displays (HMD) to present their interface to the user, an idea that Ivan Sutherland introduced in 1965 with the following words:

"The ultimate display would, of course, be a room within which the computer can control the existence of matter. A chair displayed in such a room would be good enough to sit in. […] With appropriate programming such a display could literally be the Wonderland into which Alice walked."[1]

While digital chairs are not good enough to sit in physically, immersive technologies have become considerably more mature since then (Qiao et al., 2019). However, they are still some ways off from widespread adoption.

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[1] (Sutherland, 1965, p. 508).

Virtual Reality (VR) and Mixed Reality (MR) technologies are part of the fast-growing field of immersive technologies. In contrast to VR, MR offers a unique set of features where the physical world can be annotated, adapted, and redesigned (Çöltekin et al., 2020). Therefore, immersive technologies, particularly MR interfaces, constitute a paradigm shift in how virtual content is displayed and humans interact with it (Schmalstieg & Höllerer, 2016). Information and services can be woven into perceived reality, thus making displays and traditional interfaces unnecessary – especially in a mobile context.

MR interfaces could potentially transform how mobile pedestrian navigation systems work. Even though mobile pedestrian navigation systems have become pervasive (Huang et al., 2018), their interaction model is still primarily rooted in the desktop metaphor of early personal computing (Pangilinan et al., 2019). Their interface usually evolves around apps and pages shown on a phone screen or sometimes on a watch. They are an extension to paper-based maps and offer additional benefits such as assisted route planning and turn-by-turn instructions.

Nonetheless, these navigation systems still require considerable visual and mental attention, for example, when navigating an unfamiliar city. Meaning users still have to focus on technology rather than their own goals. This contradicts Mark Weiser's (1991) vision of ubiquitous computing, which says that computers should vanish in the background. However, given the technology to understand and model user context in detail, MR interfaces promise to do precisely what Weiser (1991) envisioned. Therefore, MR interfaces have the potential to become the primary user interface for mobile, situated, and context-aware computing (Schmalstieg & Höllerer, 2016) and, thus, mobile pedestrian navigation systems.

In MR, it is possible to create "*direct, automatic, and actionable links between the physical world and electronic information*" (Schmalstieg & Höllerer, 2016, p. 18). The physical world can then be augmented with new affordances or ways of interaction. For example, turn-by-turn instruction can be embedded at relevant positions in the environment, giving the user additional digital navigational cues. Moreover, existing physical navigational cues, such as relevant landmarks, could be highlighted, informing the user about relevant existing real-world affordances. MR interfaces could therefore be a more intuitive alternative to interfaces rooted in the desktop metaphor and, correspondingly, also to digital maps.

It is evident that mixing humans' perceived reality with virtual content potentially transforms the way humans behave (Fraser & Hedley, 2018) and how they perceive the world around them (Erickson et al., 2021) – for better or worse (Rose, 2021). Instead of having to share the attention between screen and environment, MR interfaces potentially allow humans to learn about their environment while navigating without being distracted by the technology. However, they may also be overwhelmed by digital content crowding their field of view.

1.1 Motivation

When I broke my tibia and fibula while playing football, the doctors decided I needed an emergency operation in the middle of the night. Soon after arriving at the hospital, a nurse was tasked to get me to the operating room (OR). On the way there, he got lost multiple times in the labyrinth that is the University Hospital of Zurich. While I did not suffer any consequences due to time lost during the unwanted exploration of the hospital's hallways, I could not help but think about what would have happened if it had been urgent.

Liben, Kastens, and Stevenson (2002) have shown that using maps while navigating is not an easy task for children and adults because it requires an understanding of the relationships between the map (i.e., the representation of space) and the self. Yet, interactive map-based navigational aids on smart devices work sufficiently well for most users in outdoor urban and rural environments (e.g., Fonseca et al., 2021), possibly thanks to information such as accurate location and orientation information. Therefore, it is fair to say that the efficacy of mapping and navigation apps like Google Maps or Swisstopo has led to their widespread adoption in outdoor areas.

Nonetheless, pedestrian navigation is still a very active research field with many challenges. Moreover, most of it was conducted in outdoor areas (Vanclooster et al., 2016), while indoor areas were neglected, even though people tend to get lost there more often (Brunner-Friedrich & Radoczky, 2005). One reason could be that the global positioning system (GPS), the most used localization technique in navigational aids, works well in outdoor areas but not indoors. For indoor environments, which can be more complex because they often require three-dimensional movements (Karimi, 2015), there are no scalable or widely adopted solutions (Ohm et al., 2015). However, thanks to recent advances in vision-based localization techniques (e.g., Kunhoth et al., 2020; Khan et al., 2022), studies of indoor pedestrian navigation systems have become feasible.

Using interaction and visualization techniques from conventional pedestrian navigation systems could serve as an initial approach to the design of indoor pedestrian navigation systems. However, there are concerns regarding the potential detrimental impact on the acquisition of spatial knowledge resulting from excessive usage of conventional pedestrian navigation systems such as Google Maps (e.g., Klippel, Hirtle and Davies, 2010; Gardony et al., 2013; Rehman and Cao, 2017). Furthermore, users must share their attention between the device and their surroundings (Oulasvirta et al., 2005), especially in this mobile context. Therefore, mobile phone use in public places for texting or navigating is distracting and threatens the user's safety, much like when driving (Nasar & Troyer, 2013). Finally, the additional complexity of indoor spaces (e.g., people may have to switch floors) (Karimi, 2015) will not only require new visualization techniques but could also necessitate novel interfaces. MR interfaces offer a potentially great alternative to state-of-the-art navigation techniques and systems because route instructions and other geographic information can be embedded directly in the environment.

There has been a general lack of research on the human aspects of MR technologies (Merino et al., 2020). While there is some research on MR interfaces for pedestrian navigation, it usually focuses on

technical implementation, leaving little time for a thorough assessment of the actual benefits of such a system (Malaka & Benjamin, 2008). More recent papers have studied the potential benefits of MR interfaces for navigation. However, not all of them have been performed on MR HMDs but instead with smartphone-based Augmented Reality (AR) systems and found few, misleading, or no beneficial effects (e.g., Rehrl et al., 2014; Rehman and Cao, 2017; Dong et al., 2021; B. Liu et al., 2022; Morf, 2022).

It is, therefore, necessary to study the human aspects of MR technologies and conduct user studies in real-world scenarios (Merino et al., 2020), test different interaction modalities with MR content (Çöltekin et al., 2020), and study its suitability for indoor navigation. However, AR and MR are notoriously tricky mediums to work with for designers (MacIntyre et al., 2004), and researchers may lack the skills to use game engines to implement complex 3D experiments (Alsbury-Nealy et al., 2022). Hence, a sandbox environment where users can quickly create augmented territories to perform cognitive and usability experiments provides a practical basis for studying indoor navigation with MR interfaces.

1.2 Research Goals

This thesis aims to develop an application to lower the technical entry barriers for studies on MR interfaces for indoor navigation and wayfinding. Specifically, this master's thesis aims to develop a HoloLens application according to the principles of HCD. Researchers with various degrees of technical skills should be able to perform user studies related to human factors of MR as an interface to indoor navigation systems.

The application should:

a) Have a UX and UI design according to the principles of HCD.
b) Enable researchers with varying technical skills to design and perform user studies on space-time decision-making and human behavior during navigation with an MR HMD.
c) Provide functionality to visually represent geographical point data according to cartography and map design principles.

Finally, by the end of this thesis, the following artifacts should be available:

1) A deployed HoloLens Application installed on the Microsoft HoloLens.
2) A well-documented Unity Project that other contributors can expand.
3) Detailed documentation of system and user requirements of the application.
4) Appropriate documentation to extend the framework to support additional use cases of researchers.

1.3 Research Questions

As part of the process of HCD, the following research questions will need to be addressed:

a) What is the target audience of the MR application presented in this thesis, and what are their skills?

b) What are the research questions that they want to answer with the application?

c) What elements and functionality does the application need to satisfy the target audiences' needs and support them in answering their research questions? (i.e., what are the requirements of the application?)

d) Are there similar applications, frameworks, and guidelines that could serve as a starting point to inform the questions in a), b), and c)? Moreover, what are their advantages and disadvantages?

1.4 Research Context

As MR technologies modify perceived space, they are inherently geographic and thus highly relevant for research in geographic information science (GIScience). This interdisciplinary thesis contributes to research in user-centered GIScience and Geovisualization, as well as human-computer interaction (HCI), specifically Ubicomp. It uses methods from HCD to build an application to study and assess the usability and design of MR interfaces in the context of navigation and wayfinding in indoor environments.

2 Background

2.1 Human Navigation

Navigation was defined by Montello (2005, p. 2) as a "*coordinated and goal-directed movement through the environment by organisms or intelligent machines*". To navigate, humans use their cognitive abilities to plan and execute an efficient movement using their motor abilities. These two processes are referred to as wayfinding and locomotion (Montello, 2005).

Locomotion is "*the movement of one's body around an environment, coordinated specifically to the local or proximal surround*" (Montello, 2005, p. 5). Wayfinding, on the other hand, refers to "*the goal-directed and planned movement of one's body around an environment in an efficient way*" (Montello, 2005, p. 5). Efficiency in this context does not always refer to navigation speed. Though humans often optimize routes for navigation speed, other factors such as safety, legality, or enjoyment may play a crucial role while humans perform wayfinding. In other words, people must be aware of potentially hazardous or prohibited areas, or they may want to increase their enjoyment (e.g., while hiking).

To perform wayfinding, humans first need to know where they are and the direction they face. Then they can plan a route depending on an understanding of where their destination is located and execute their plan (Ishikawa et al., 2008). During the process, they repetitively use perceived environmental information in the form of landmarks or recorded external representations (Golledge, 2003) in combination with remembered internal environmental information, for example, in the form of a previously acquired cognitive map (Passini, 1981).

2.1.1 Cognitive Maps

Tolman (1948) coined the term cognitive map to refer to the internal representation of information about physical space in humans and other species. It implies a conscious encoding of spatial information determining one's current position and how that relates to other objects in the surrounding space (Golledge, 1999). This spatial information is the basis of navigation in many species. It enables homing or path following and may also facilitate sharing spatial knowledge or other actions requiring route recall or layout knowledge (Golledge, 2003).

To do the systematic errors in spatial knowledge of humans and the accurate representations of the spatial relationships between elements in familiar environments justice, more recent literature also used the term cognitive collage and spatial mental model to refer to mental representations of environments in humans (Tversky, 1993).

2.1.2 Landmarks

According to Golledge (1999), landmarks can be described as significant natural and humanmade objects that stand out from their surroundings or as reference points (destinations or waypoints) that aid humans in navigating. Finding a location necessitates information about route segments and turns along the route (Downs & Stea, 1973). Landmarks are, therefore, inherent for human navigation (Sorrows & Hirtle, 1999) because they provide a reference from which humans can derive, segment, and turn knowledge.

2.2 Navigational Aids

As established above, landmarks and the environment are critical cues for humans to navigate familiar and unfamiliar environments. Whether star constellations guiding explorers over the oceans, sea ice and snow conditions enabling Inuit to navigate large ice deserts, or famous skyscrapers helping tourists remember the way back to their hotel, they can be crucial for humans to reach their destination. However, the process of perceiving, remembering, and reasoning about space, may take multiple attempts or break down entirely.

The reasons are manifold; humans may fail to perceive essential environmental information to determine their location and heading, and they may lack the necessary knowledge of their surroundings either due to a lack of internal (i.e., have an insufficient mental model or understanding of relevant cues) (Vanclooster et al., 2016) or external (e.g., no access to a map) representations of space (Ishikawa et al., 2008). Moreover, they may have poor navigational skills rendering them unable to remember or understand the relationships between a representation of space and their perceived environment (Ishikawa et al., 2008). Finally, they may just be in an obfuscating environment void of any actionable environmental information (e.g., a maze or the University Hospital of Zurich) (Dalton, 2003).

A navigational aid may be used to prevent slowdowns and breakdowns during the navigation process (Golledge, 1999). Such tools are omnipresent nowadays, from simple you-are-here floor plans to sophisticated digital navigational systems. Thanks to GPS, the permanent availability of smart devices, big data, and location-based services (LBS), such digital navigational aids have become more sophisticated and popular (Rehrl et al., 2014).

2.2.1 Pedestrian Navigational aids

The first consumer navigational systems were developed with car navigation in mind; however, interaction techniques borrowed from these devices do not apply to pedestrian navigation (Ohm et al., 2015). Consequently, the interface design of pedestrian navigation systems has become the center of considerable research in the past 20 years (Ohm et al., 2016). Various presentation formats of such spatial information have been developed, from verbal navigational directions to static or interactive maps, 3-D visualizations, and animations (Montello et al., 2004).

Modern Navigation Systems assist their user in route planning and give route instructions, generally at intersections. In contrast to navigation systems used in cars, where route instructions are usually given based on measured distance specifications (e.g., turn right in 500m), pedestrians prefer route instructions based on landmarks, often also referred to as salient objects (Hölscher et al., 2006; May et al., 2003; Miller & Carlson, 2011; Raubal & Winter, 2002). An additional difficulty in designing pedestrian navigation aids is that pedestrians generally have more options than cars when locomoting, as they can use most types of roads, cut across open spaces like parks, or enter buildings (Stark et al., 2007).

2.2.2 Complexities of indoor navigation (systems)

As mentioned above, pedestrians can move seamlessly between outdoor and indoor spaces. While human indoor and outdoor navigation is conceptually alike – They both involve the same activities and cognitive processes – there are spatial differences that lead people to get lost there more often (Brunner-Friedrich & Radoczky, 2005). While outdoor environments generally only require a two-dimensional understanding of space, indoor environments often require a three-dimensional spatial sense (Karimi, 2015). Moreover, Indoor environments can often be devoid of any salient objects (Brunner-Friedrich & Radoczky, 2005), and building structures can be non-uniform (e.g., different layouts on different floors) (Karimi, 2015).

In addition to these design challenges, the lack of suitable indoor localization techniques (GPS is often not accurate enough or does not work at all) (Kunhoth et al., 2020), the unavailability of consistent indoor geographic data, and challenges with the structure of data models (Lorenz et al., 2006) have prevented indoor navigation aids from being used more widely.

Even though recent advances in indoor localization and modeling techniques (Khan et al., 2022) have made indoor navigation systems attainable, research into their design is still relatively sparse. Some researchers focused on integrating indoor navigation systems seamlessly with existing outdoor systems (Vanclooster, van de Weghe, and de Maeyer, 2016). Others have focused on dealing with the unavailability of salient objects (Brunner-Friedrich & Radoczky, 2005) and the implications for map design (Puikkonen et al., 2009) and route instructions (de Cock et al., 2019; Ohm et al., 2017). Their results show that indoor navigation systems require novel designs and that learnings and techniques from outdoor pedestrian navigation systems should be applied with caution.

2.2.3 Effects on Spatial Learning

To further understand the importance of novel designs and approaches to indoor pedestrian navigation systems, it is important to highlight the effects the excessive use of state-of-the-art pedestrian navigation systems has on spatial learning. Even though these outdoor pedestrian navigation systems can be successful in terms of navigation speed and success, people are less likely to get familiar with a novel environment or retain a route after completion (e.g., Péruch and Wilson, 2004; Parush, Ahuvia and Erev, 2007).

While using mobile pedestrian navigation systems, people have been found to process less of their surroundings (Klippel et al., 2010). Similarly, they tend to rely too heavily on the instructions given by the system (Parush et al., 2007), resulting in longer navigation task completion times or even serious accidents when the automation fails. Therefore, novel designs that facilitate spatial learning or even teach people to build better mental models of space are required not only for indoor navigation systems but also for pedestrian navigation systems in general.

As previously discussed, landmarks are central to human navigation and facilitate the construction of cognitive maps and the recall of route segments and turn knowledge. For example, Wunderlich, Grieger and Gramann (2022) have just recently found that including landmark information in auditory turn-by-turn instructions leads to lasting route knowledge. Yet, how to meaningfully visualize landmarks on mobile maps so that users can create the necessary links between the map and the environment and improve spatial learning is still little explored (Kapaj et al., 2021).

Finally, as people have to divide their attention between the map and their surroundings to create links between the map and the environment while consuming turn-by-turn instructions on a mobile phone (Gardony et al., 2013), other interface technologies for indoor pedestrian navigation should be considered. MR interfaces could potentially remedy many of these issues.

2.3 Mixed Reality

Milgram and Kishino (1994) popularized the term mixed reality to broadly refer to interfaces that merge the physical world with virtual worlds. In other cases, similar interfaces are termed Augmented Reality (AR). However, in 1994 the term augmented reality was seemingly exclusively used for MR presented with a HMD (Milgram & Kishino, 1994). In contrast, Azuma (1997) explicitly defines AR independently from specific display technologies as an interface with the following three characteristics:

- A system that combines the physical and some virtual worlds.
- A system that is interactive in real-time.
- A system that is registered in 3D space.

Similarly, the term AR nowadays also refers to smartphone-based systems that satisfy the conditions above. On the other hand, the definition by Çöltekin *et al.* (2020, p. 4), according to which MR, in contrast to AR, "*suggests that there is real-time spatial referencing (i.e., spatial computing), thus virtual and real objects are in the same spatial reference frame, and meaningful interactions between them is possible*" seems fitting for the geographic context at hand. Therefore, and for consistency reasons and not because I have a specific argument that settles the confusion or favors either term, I will use MR to refer to these interfaces for the rest of the thesis.

Considering the three characteristics above, MR technologies constitute a paradigm shift in how virtual content is displayed and humans interact with it (Schmalstieg & Höllerer, 2016). Information and services can be weaved into perceived reality, with any necessary hardware vanishing in the

background. Then, people can use them without thinking, and they may focus on new goals (Weiser, 1991). If cyberspace is mixed with the physical environment, computing will become ubiquitous, as imagined by Mark Weiser (1991) and the researchers at Xerox PARC.

At this stage, it is still key to note the differences between MR and VR. In VR, the user is fully immersed in a synthetic environment, cannot see or hear, and, in extreme conceptualization, does not even feel the real world (R. T. Azuma, 1997). Therefore, VR contrasts Mark Weiser's (1991) vision of ubiquitous computing (a virtual world is only a simulation rather than an enhancement of the natural world). MR technologies, on the other hand, offer an interface that promises to do what he envisioned: the computer vanishing in the background. Hence, MR has the potential to become the primary user interface for situated and context-aware computing (Schmalstieg & Höllerer, 2016).

2.3.1 Interface technology

Smartphone-based MR made a splash in 2016 when Pokémon Go, a location-based MR game, was released. Yet, smartphones are monitor-based, non-immersive video displays and act like a window to the MR world (Milgram & Kishino, 1994). On the other hand, a HMD immerses the wearer fully into the MR world. This is a fundamental difference as users have their hands free and can potentially interact with the MR world much like they would with the physical world. Therefore, this thesis focuses on HMDs as the interface technology for MR.

Head-mounted Displays

Ivan Sutherland (1965) is famously credited with developing the first MR HMD in 1965. HMDs are devices worn on the head, sometimes called smart glasses, due to their visual similarity with corrective glasses. HMDs can be used to display both MR and VR content.

On an MR HMD, Virtual content is superimposed onto the physical world either with optical see-through or video see-through technology (R. T. Azuma, 1997). On optical see-through HMDs, the digital content is projected onto a semi-translucent carrier in front of the wearer's eyes, allowing them to see both the virtual and physical world simultaneously (R. Azuma & Bishop, 1994). Video see-through HMDs, on the other hand, capture a stereoscopic view of the physical world with video cameras and combine the virtual and physical world into an image that is then presented on displays inside the HMD (Edwards et al., 1993).

The HoloLens, used as a platform for the application presented, is an OST HMD. These types of HMDs typically have lower resolution compared to VST HMDs and may not be able to display as advanced graphics. However, a key advantage of OST HMDs is that the user can still see the real world even if the device malfunctions and does not become completely blind (Rolland et al., 1995).

SLAM, Inside-out tracking and VIO

While both technologies have advantages and disadvantages, they require technology to co-register the physical and digital worlds. On an HMD, this is usually achieved through Simultaneous

Localization and Mapping (SLAM). SLAM allows a device to simultaneously build a map of its environment and determine its position within that map (Aukstakalnis, 2016).

To use MR interfaces in a mobile context, SLAM is achieved through inside-out tracking, a technique to determine the position and orientation of the device without external sensors and markers (Aukstakalnis, 2016). Other tracking technologies, such as GPS, are usually not accurate enough (Note: GPS uses outside-in tracking because it requires signals from satellites to determine the device's position). Moreover, many areas lack virtual models (e.g., most indoor spaces) of the physical world to co-register both worlds.

According to Pangilinan, Lukas, and Mohan (2019), monocular visual-inertial odometry (VIO) is the only technology capable of providing accurate tracking for a satisfactory user experience in MR. A VIO system uses RGB or sometimes RGB-d (i.e., depth) camera(s) and an inertial measurement unit (IMU) to perform SLAM (Pangilinan et al., 2019). In conclusion, the technological foundations of MR systems have been laid, and technical aspects have received a lot of attention in the literature (Merino et al., 2020). Conversely, questions of UX and UI design in MR are still scarcely treated in the literature and will require more attention in the future.

2.3.2 Interface design and human aspects of MR

As they have matured, interest across multiple domains to adopt and research MR systems has proliferated (Suh & Prophet, 2018). While the construction and planning industry (Rankohi & Waugh, 2013) were early adopters, other fields such as education (Brij & Belhadaoui, 2021), medicine (Roessel et al., 2020) or marketing and business (Yussof et al., 2019) have started to investigate MR as an interface for specific use cases.

Thus, questions involving human aspects have already gained importance on the MR research Agenda (Suh & Prophet, 2018). However, most often, approaches that boost users' performance are considered most effective, even though other cognitive aspects (e.g., perception, emotion, presence, cognitive load, attention, learnability, and memory) might play an equally important role in the effectiveness of MR interfaces (Merino et al., 2020).

Interaction paradigms

Currently, the output of a state-of-the-art MR system acts on two of the five senses; visual and auditory (see, e.g., HoloLens). Although there is already considerable research on haptic output (i.e., feedback) beyond vibrating controlling devices (Benko et al., 2016), it has not yet made its way into commercially available products. To be a fully interactive system, MR must also be able to accept and understand human input. However, traditional interface metaphors, such as "Windows, Icons, Menus, Pointers" (WIMP), only work when a physical screen is simulated in MR. Therefore, an MR system requires different input modalities. Çöltekin *et al.* (2020) recognize potential in voice-based, movement-based, gaze-based, or controller-based input modalities.

However, even though the input modalities are essential for the users of the application discussed in this thesis, the application is primarily geared towards studying system output (i.e., what an

experiment participant sees and not how they interact with it). The study of input modalities in an MR system might be more relevant for research in Human-Computer Interaction (HCI) rather than GIScience.

2.4 Mixed Reality and Geovisualization

The output of an MR system can make invisible spatial phenomena perceivable in situ and in real time (Fraser & Hedley, 2018). MR lets users consume and modify geographic information directly in the field (Hugues, Cieutat, & Guitto, 2011), among others, via a visual, auditory, or haptic interface (Peddie, 2017) embedded in the space around them. It is possible to create "*direct, automatic, and actionable links between the physical world and electronic information*" (Schmalstieg and Höllerer, 2016, p. 18). As MR technologies modify perceived space, they are inherently geographic and thus highly relevant for research in geographic information science (GIScience).

However, research about cognitive and usability issues (i.e., input and output of the interface) of MR in augmented territories is still relatively scarce. In a literature review on MR by Merino *et al.* (2020), only about 12% of the papers reviewed discuss human factors in mobile MR – though the number of

Figure 1: An example of an augmented map: An interactive 3D visualization of a river displayed on a tabletop. (Netzwelt, 2022)

papers has sharply increased in the last few years. Moreover, while there are initial approaches, it remains unclear which interaction modalities are best suited and how the interaction with MR content should best be designed (Cipresso et al., 2018). Thus, studying the implications of MR for geographic information systems (GIS) and geovisualization could yield beneficial results in these fields (Hugues, Cieutat, & Guitto, 2011).

2.4.1 Augmented Map and Augmented Territory

Hugues, Cieutat, and Guitton (2011) propose differentiating between augmented map and augmented territory when considering MR applications. The term augmented map refers to GIS data visualized with an MR interface irrespective of the user's current location. In an augmented territory, on the other hand, the target of the augmentation is not to create a representation of the environment but the environment itself. An example of an augmented map would be an interactive 3D visualization of a meandering river displayed on a tabletop (Figure 1). Pedestrian navigation, where route instructions are embedded seamlessly in the environment, on the other hand, is a perfect example of an augmented territory. Consequently, the focus of the application presented in this thesis will be to build augmented territories. In other words, the goal of the application will be to answer what happens to people when the environment becomes the map.

2.5 Pedestrian Navigation and Mixed Reality

As outlined above, there is a lack of research about how MR interfaces on HMDs can provide additional value over traditional desktop or mobile interfaces in GIScience, especially for pedestrian navigation systems. Likewise, there is little research about whether and how an MR interface can improve indoor wayfinding and spatial learning over physical navigational aids (e.g., you-Are-Here map) or mobile touch interfaces.

Therefore, to understand the requirements to study indoor navigation, wayfinding, and spatial learning in MR and how to develop a valuable application to do so, it is crucial to understand three things:

- What kinds of potential studies and research questions are needed to fill my identified research gaps?
- What tools are needed to perform such studies, and more specifically, how could the HoloLens be used to perform these studies?
- Who performs those studies (i.e., who is the target audience of the HoloLens in my case)?

The second two questions will be discussed in the requirements research phase of the first iteration because they are more related to requirements engineering and human-centered design rather than the background of this thesis.

2.5.1 Existing Experiments

The application developed during this thesis should support various use cases and enable researchers without extensive programming knowledge to perform indoor navigation studies with an MR HMD. To achieve that, it is essential to understand the potential use cases, in other words, have knowledge of the domain of research questions that will be studied using the framework. While the resulting list of possible research questions will not be complete, it serves as a guide to determine the application's features and their importance.

To understand relevant research questions and to come up with potential research questions that can be studied with the application described here, I gathered a non-exhaustive list of pedestrian navigation and wayfinding experiments with interactive navigation systems. I decided to group them into three tables:

- Table 1: Experiments with handheld map-based pedestrian navigation systems
- Table 2: Experiments with handheld AR/MR pedestrian navigation systems
- Table 3: Experiments performed with a pedestrian navigation system on MR HMDs

On the one hand, experiments performed with handheld devices (Map-based or AR systems) could inform similar experiment designs with an MR HMD. On the other hand, experiments with MR HMDs either point to additional research gaps or can inform further, more specific, in-depth studies.

Handheld digital navigation experiments

Table 1 shows a selection of experiments with digital pedestrian navigation systems on handheld devices. From these papers, I identified three principal aspects that will be important for the application at this stage:

- **Route instructions:** Their style and design.
- **Hardware:** The device and interface used to present the route instructions.
- **Evaluation criteria:** The criteria for which these designs are tested.

Even though a systematic, more extensive literature review would be needed to make definitive statements, the experiments show trends in both the design of route instructions and the variables for which these designs are evaluated.

Route instructions are presented turn-by-turn or as route sketches on maps. The studies were mainly performed using handheld devices, giving visual and, in some cases, verbal instructions. Some papers explore haptic route instructions (e.g., Azenkot, Ladner and Wobbrock, 2011; Montuwy, Dommes and Cahour, 2019); however, they are less relevant than visual or verbal instructions in the context of this thesis. Visual instructions were given in the form of textual instructions, 2D or 3D symbols on large-scale map extracts, within 3D models showing the user's current environment, or even within photographs. Finally, route sketches are presented on 2D or 3D maps in various levels of abstraction as well as on satellite imagery. Figure 2 shows a summary and classification of given route instructions.

In most of the papers in table 1, the designs are tested for navigation speed and success rate. While these are not the only variables relevant in navigation, it seems essential to establish the speed and success rate of novel designs compared to an existing system to determine their chances for user acceptance. This appears to be in line with a survey by Fonseca et al. (2021), where 41,9% of respondents indicated that selecting the shortest routes was the main reason for using a pedestrian navigation system, and 38,1% of them used the system to find specific, unknown locations (e.g., restaurants). Even though the motivation to use a system is a crucial factor in understanding the

utility of a system, other factors of which users are unaware can be equally central to the understanding of the utility of a system.

Table 1: A non-exhaustive list of experiments with handheld map-based pedestrian navigation systems.

Short Experiment Description	Paper
Comparison of different route instruction types (textual and spoken instructions, 2D route sketches, 2D maps, pseudo-realistic instructions (i.e., 3D maps)) on mobile devices for outdoor pedestrian navigation in an urban environment.	(Kray et al., 2003)
Between-subject comparison of navigation speed with a map-based mobile navigation system and a navigation system consisting of textual route instructions and photographs of the user's current location.	(Beeharee & Steed, 2006)
Comparative field evaluation of navigation speed and usability with photograph-based AR and map-based systems (both on a handheld device).	(Malaka & Benjamin, 2008)
In-situ comparison of pedestrian navigation performance (information effectiveness (e.g., number and reasons for stops), efficiency (walking and task completion time, duration of stops), and user satisfaction with both a mobile map-based and mobile AR navigation system.	(Rehrl et al., 2014)
Comparison of a pedestrian navigation system that communicates route instructions based on user gaze at a decision point with a map-based turn-by-turn pedestrian navigation system for navigation performance (i.e., speed and success), spatial learning, and user experience in a 3D environment.	(Giannopoulos et al., 2015)
Two user studies that compare interface designs for an indoor navigation system that shows route segments and landmarks and one that additionally shows floor plans using an eye-tracking system to determine navigation speed and visual attention on the navigation system.	(Ohm et al., 2017)

Between-subject comparison of four different pedestrian navigation systems and their effects on self-localization and allocation of attention during wayfinding in a real-world environment (i.e., How do different pedestrian navigation systems affect spatial learning?).	(Brügger et al., 2019)

In addition to the two criteria mentioned above, the experiments listed in table 1 use pre-tests to determine the user's spatial ability and post-experimental questionnaires or interviews to determine user preference, acceptance, perceived difficulty of the tasks, reasons for errors, and readability of instructions. Moreover, they also used questionnaires to assess route perspective and survey knowledge gained by users. Finally, researchers used eye-tracking devices to analyze the users' visual attention and to present specific route instructions at a decision point.

Most experiments were performed "in the wild" outside with a handheld device (smartphone, tablet, or in some cases, a laptop). However, Giannopoulos, Kiefer and Raubal (2015) used a virtual environment displayed on a projection wall where participants moved in the environment by using a joystick. Like the experiment by Giannopoulos, Kiefer and Raubal (2015), experiments to study human wayfinding behavior are often performed in virtual environments using either a projection wall or, more recently, VR goggles to display the environment (e.g., Doner et al., 2022 for a recent example).

Table 2: A non-exhaustive list of experiments with handheld AR/MR pedestrian navigation systems

Short Experiment Description	Paper
Explorative user study about when people use the AR functionality in an otherwise map-based digital navigation aid.	(Mulloni et al., 2011)
Comparison of navigation with a digital map to navigation with information from an AR browser (and a combination of both) for completion time and user preference.	(Dünser et al., 2012)
Presentation and preliminary user experience study of an AR navigation system using observation techniques and questionnaires.	(M. J. Kim et al., 2015)
Quantitative comparison of a smartphone-based AR navigation aid with electronic maps for wayfinding performance, visual attention, and route memory.	(Dong et al., 2021)

Qualitative usability study of a 3D landmark-based map interface, which should support location awareness and spatial knowledge acquisition.	(Zhang & Nakajima, 2021)

Handheld MR Navigation Experiments

Unlike the experiments presented in table 1, the experiments in table 2 (MR navigation experiments with handheld devices) are mostly explorative and qualitatively investigate different aspects of the system's user experience. Most of them also only present preliminary results. Mulloni, Seichter and Schmalstieg (2011) hypothesize, for example, that an AR interface could be helpful at specific stages during navigation. They find that AR usage increases just before an intersection (decision-making) and shortly after (decision confirmation). Only Dünser et al. (2012) and Dong et al. (2021) evaluate their designs for task completion speed and success. However, all papers report on user satisfaction and experience.

In the experiments in table 2, route instructions were presented in the form of 2D (snapped to real-world surfaces) (Mulloni et al., 2011) or 3D arrows (M. J. Kim et al., 2015), continuous lines embedded in the environment (Dong et al., 2021) and highlighted target landmarks without a description of the actual route (Dünser et al., 2012; Zhang & Nakajima, 2021) which can be referred to as a beacon-based approach to navigation.

MR HMD Navigation Experiments

Finally, table 3 shows navigation experiments performed with MR HMD-based navigation systems. Much like table 1 and table 2, the list here is incomplete but should indicate trends to determine the application requirements presented in this thesis. Again, the three principal aspects of the experiments were how the route instructions were presented, the hardware used, and the criteria for which the systems were tested.

While early experiments were almost exclusively performed on custom-built prototypes, most of the recently published experiments in the list were performed using the Microsoft HoloLens, indicating that it seems well suited to conduct academic research. Of the papers using the HoloLens to perform their experiments, one used the built-in 3D Viewer App (Morf, 2022), two built place-specific fixed routes (Liu, Ding and Meng, 2021a; B. Liu et al., 2022), and one created a fully functional navigation system to find specific items in a food store (Bågling, 2017).

Table 3: A non-exhaustive list of experiments performed with a pedestrian navigation system on MR HMDs.

Short Experiment Description	Paper
Presentation of a research prototype to explore issues in user interface design (Although technically not an experiment, I deemed it essential to include as it provides an insight into the early challenges of MR pedestrian navigation systems).	(Feiner et al., 1997)
Study on the suitability of an HMD for navigation in low visibility conditions. The custom-built prototype was evaluated for navigation speed and accuracy, travel distance, and user preference.	(Wilson & Wright, 2009)
Comparison of an MR indoor navigation system on an HMD (google glass) with a smartphone-based system and paper maps for navigation speed, navigation success, workload, and route retention.	(Rehman & Cao, 2017)
Description of the design of an indoor navigation system and usability test determining navigation speed and user preference concerning the visual design.	(Bågling, 2017)
Experiment on the effects of virtual semantic landmarks on spatial learning.	(B. Liu et al., 2021)
A user study of the effects of incorrect virtual information on the users' perception of the environment and the effects of distinct route instructions compared to a connected path on mental load.	(B. Liu et al., 2022)
Examines how background information on physical landmarks given in an MR environment can affect spatial learning during wayfinding.	(Morf, 2022)

In the experiments performed with MR HMDs, route instructions were either given by showing a virtual map of the environment in the corner of an eye (Wilson & Wright, 2009) or by embedding 3D objects in the environment (all others). Embedded 3D objects could be cones pointing at a target (Feiner et al., 1997), arrows pointing in the target direction (B. Liu et al., 2021; Morf, 2022; Rehman & Cao, 2017), a continuous line indicating the path (Bågling, 2017) or a combination of arrows and lines (B. Liu et al., 2022). Moreover, J. Liu et al. (2022) used a novel, beacon-based approach where users received no route instructions but were shown a digital representation of a physical landmark

regardless of its current visibility. However, this paper was not included in table 3 because the experiment was performed in a VR environment instead of with an MR HMD.

Like the experiments performed with screen-based pedestrian navigation systems in table 1, most designs used in the experiments of table 3 were tested for navigation speed and success rate. Moreover, questionaries or interviews were used to determine user satisfaction and acceptance after using the system and test their gathered spatial knowledge during the experiment.
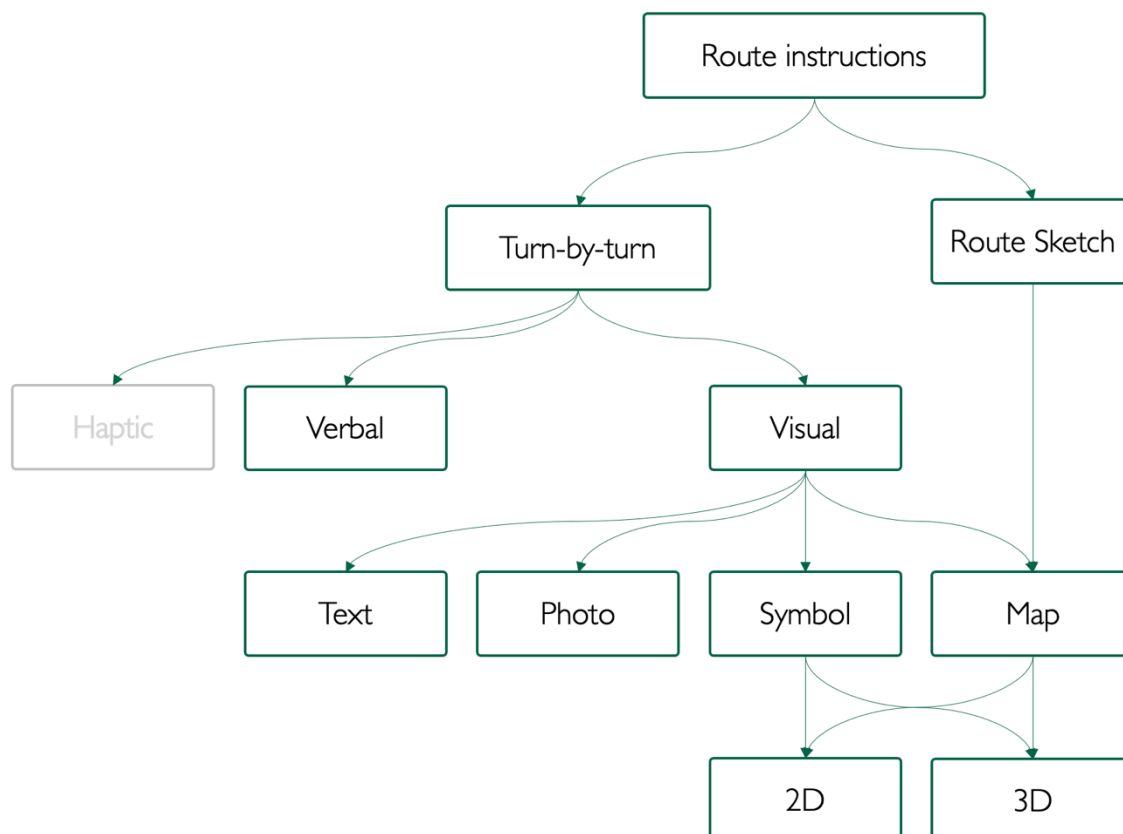
Figure 2: Classification of the types of route instructions used in the experiments listed in tables 1 − 3.

2.5.2 Classes of potential studies

As the last section's analysis shows, there are many possibilities to present route information to users and even more ways to evaluate navigation systems. Therefore, the application should enable as much experimental research as possible, independently of the applied method. The framework should, thus, for example, neither force a qualitative nor a quantitative approach. However, it should probably, at some point, facilitate built-in data collection for some quantitative experiment designs. As a result, potential studies conducted with the application can broadly be categorized into the following classes:

- **User-centered studies:** Investigating the benefits, drawbacks, or potential sources of harm of an MR navigational interface for specific user groups such as older adults, children, or people with disabilities.
- **Interface-centered studies:** Comparing the usage of different navigational aids such as signage, you-are-here-maps, or interactive interfaces to MR HMDs for variables such as speed, convenience, or cognitive load during wayfinding.
- **Task-centered studies:** Study the suitability of an MR HMD navigational system for specific tasks that entail wayfinding, such as evacuation, exploring a new environment, or finding a book in a library.
- **Design-centered studies:** Exploring how the design of an MR navigational system (e.g., guidance with arrows, continuous lines, or highlighted landmarks) affects the effectiveness of the system, the user's experience, or their sense of orientation within an environment

Most experiments will be user-centered to some degree, and researchers may study a combination of these classes. Yet the classification above is meaningful as each of the classes will require a specific set of features.

2.5.3 Potential Experiments

It is crucial to understand the research questions researchers might want to answer with the help of the application presented in this thesis. In the end, this section will help identify potential features and functionality that may be useful or necessary. To ensure that they can then help to inform specific requirements for the framework, they are grouped in the classes mentioned above. This list is neither a complete list of relevant research questions to study navigation with MR HMDs, nor will the final application ensure that all these can be answered.

The papers above show that task completion time and success are essential baseline variables to study when testing novel navigational aids. The likelihood of adoption is low if these do not match or improve upon existing systems. In addition to these basic performance measures, any other potential barriers to adoption, such as user experience or the learning curve required to use the system, should be considered for all navigation studies with MR HMDs.

User-centered

For user-centered experiments, in addition to the basic performance measures mentioned above, relevant crucial factors emerging from the mobile context in which the interface is used include system safety, comfort, accessibility, and reliability (e.g., Nielsen, 1993b). While these aspects are relevant for MR usability irrespective of context, comfort and especially safety are crucial elements during navigation with a navigational aid as it can be a source of distraction (Thompson et al., 2012).

To prevent distraction, novel interfaces should reduce the cognitive load during navigation. Kim and Wohn (2011, p. 1051) found that "*AR navigation was visually and temporally more demanding*" than a map-based navigation approach in a VR driving experiment. Moreover, Buchner, Buntins and Kerres (2022) find conflicting results in their literature review on the impact of AR on cognitive load and

performance. In some cases, AR applications may unnecessarily increase cognitive load, whereas, in others, they may positively influence performance and cognitive load.

It is, therefore, crucial to understand whether AR-based navigation aids could reduce cognitive load while keeping or increasing performance compared to other navigation strategies. Moreover, a detailed understanding of the characteristics of users for which specific designs might positively affect cognitive load and performance will be crucial to design useable MR navigational aids.

Examples of research questions

- Is navigating with a turn-by-turn navigation system on an MR HMD cognitively more demanding than navigating with a map-based system on a smartphone?

- Does navigating with an MR turn-by-turn navigation system on an MR HMD reduce the user's cognitive load compared to a similar AR system on a smartphone?

- How could an MR navigation system on an MR HMD help visually impaired people to improve their spatial knowledge and assist them during wayfinding?

Interface-centered

Interface-centered studies explore the advantages of MR HMDs over other interfaces, such as touchscreens. They should therefore revolve around how the user interacts with the system and how different interfaces affect not only user performance for the target objective (reaching the goal in time) but also secondary objectives such as user preference, comfort, and acceptance of the interface.

Here different interaction techniques, such as hand controllers, voice interactions, or hand tracking, will become necessary. While these are not specific to the context (navigation system) for which this framework is developed, likely, some interaction techniques work better than others for this context.

Examples of research questions

- Which interaction techniques yield the highest speed, convenience, and user preference when specifying the goal for a new route?

- Do users need feedback to confirm that they are still following the specified route and if they do, what type of feedback do they need/prefer?

Task-centered

Task-centered studies investigate the benefits an MR HMD can bring for specific navigation tasks and the contexts in which they are performed. While the primary task of navigating is often to reach the target as quickly as possible, secondary tasks and goals, such as spatial learning or exploring an environment, are equally important. Moreover, environmental factors such as low visibility or human factors such as stress may affect user performance while performing the navigational task.

Examples of research questions

- Does navigating with an MR HMD require less cognitive attention, and if so, can the freed resources be used to acquire more spatial knowledge and build a more accurate mental representation of space?

- How can navigation systems on an MR HMD be used to enable users to faster build more accurate and valuable mental representations of space?

- Can digital landmarks replace physical landmarks as references for navigation in landmark-sparse environments, and if they can, what happens when they are suddenly gone?

- Can route instructions given by an MR HMD lead to faster decision-making in stressful environments?

Design-centered

MR could radically change how navigational aids are designed. MR interfaces could undoubtedly be used to display a map in a strategically fitting position of the field of view (Like, for example, in Wilson and Wright (2009)) – Rudi et al. (2016) have, for example shown that head-based interactions with maps in MR significantly outperform haptic interactions. However, MR interfaces potentially enable other navigational support strategies. These strategies may, for example, leverage the physical environment and create direct links between physical landmarks and digital route instructions, helping or triggering users to build mental relationships between the physical environment and a digital or mental map.

Design-centered studies focus on the placement and type of route instructions and whether there are other means to guide the user through a complex environment that do not require specific route instructions but let the user make their own decisions.

Examples of research questions

- What are the effects of densely (e.g., every two meters) and sparsely (e.g., only at decision points) placed route instructions in a navigational aid on an MR HMD not only on basic performance measures but also on cognitive load and spatial learning?

- What are the effects of textual and symbolic (e.g., arrows) route instructions placed in the environment on cognitive load and spatial learning?

- Do other approaches that do not rely on turn-by-turn instructions, such as virtually emphasizing relevant physical navigational cues such as landmarks or signage, yield enough performance for users to adopt them, and do they bring other advantages over turn-by-turn systems, such as improved spatial learning?

- Does a beacon-based approach where relevant physical landmarks currently not visible are digitally made visible lead to equal or better task completion time and rate than a turn-by-turn system, and does it bring other advantages, such as smaller cognitive load and more attention to the environment?

3 Methodology

This thesis aims to develop an application framework to lower the technical entry barriers to studying and evaluating MR interfaces for indoor navigation and wayfinding. I used methods from computer science, mainly from HCI, HCD, and software development. Since this project is explorative – or
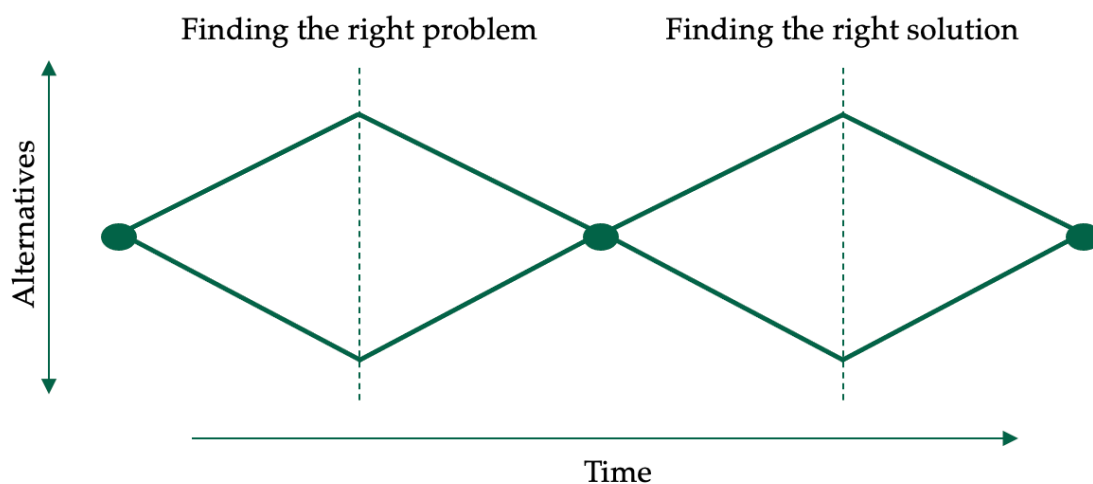
Figure 3: The double-diamond model of design as adapted from the British Design Council (2020)

formative – I will use an iterative design thinking approach outlined by Don Norman (2002). Like in the double-diamond model of the design outlined by the British Design Council (2020) (Figure 3), the goal is first to find an accurate problem description and then iteratively provide continuously tested solutions.

3.1 Human-Centered Design

Human-centered design (HCD) is an approach to designing a product or service that focuses on the end user's needs, wants, and limitations (D. A. Norman, 2002). A system must be deemed acceptable to use by the intended target audience to be successful. System acceptability is a function of social acceptability and practical acceptability. Furthermore, practical acceptability is a function of a product's cost, reliability, and usefulness, and finally, a product's usefulness is a function of its utility and usability (Nielsen, 1993c).

Therefore, designing a system accepted by the intended target audience requires a comprehensive understanding of the end user and, ideally, the user's active participation throughout the design process. The goal is to create a product or service that is both useful and usable for the intended target

audience (D. A. Norman, 2002). As mentioned in section 1.2 the product of this thesis will be an application to study virtual route instructions and 3D landmarks in MR. Therefore, I will use the term application instead of product in the coming sections, even though the described methods can be used to design and develop any product, from physical signposts to holographic route instructions.

3.1.1 Principles of Human-Centered Design

According to Rubin and Chisnell (2008), the principles of HCD are:

- An early focus on users and their tasks.
- The empirical measurement and testing of application usage.
- An iterative approach to the design of the application.

These principles are reflected in my choice of methods, as described in the following sections.

3.1.2 Target Audience

The target audience (or sometimes target user if referring to a single person) is the group of people who ultimately use the application designed during the HCD process. The target audience can consist of millions of people with diverse needs and wants or a small group with particular expectations. Understanding the needs and capabilities of the target audience is the basis for an application that solves a problem as defined in a problem statement (D. A. Norman, 1986).

3.1.3 Utility

The utility refers to an application's ability to solve the target audience's goals (Grinstein et al., 2003). It is influenced by the set of features and capabilities an application has, its performance, reliability, and ease of use (Grudin, 1992). Therefore, an application must meet the user's needs, wants, and requirements to have utility. This can mean that the application provides a new solution to a problem or offers an improvement over an existing alternative (Heskett, 2005). It is crucial for the target audience to grasp and appreciate an application's utility to adopt it into their workflow.

3.1.4 Usability

In contrast to utility, usability refers to how easy it is for the target audience to reach their goals with an application (Whiteside et al., 1988).

> *"A potentially useful system can be unusable.*
> *A usable system - one that is easily learned and handled - can be useless, serving no recognizable purpose."[2]*

Jakob Nielsen (1992) determined that the five main usability characteristics are:

1. **Learnability** – How quickly does the target audience understand the product and learn to use the application?
2. **Efficiency** – How efficiently can the target audience use the product?
3. **Memorability** – How well can the target audience pick up where they left off?
4. **Error Frequency and Severity** – How often does the target audience make mistakes when using the product, and how serious are they?
5. **Subjective Satisfaction** – How much does the target audience enjoy using the product?

It is important to note that Nielsen (1992) did neither rank nor prioritize any single aspect but instead emphasized that they should be prioritized following user research. Like utility, usability central to the user's motivation to adopt and use an application.

3.2 Design Thinking

I decided to use a design thinking approach to structure my work and develop a framework that can be successfully used to study MR interfaces for indoor navigation. Design thinking is an iterative problem-solving approach to product design. It has roots in aspirations to "scientize" design in the 1920s and 1960s (Cross, 2001). It converged out of ideas from experts like architect Buckminster Fuller, design theorist Horst Rittel, and social scientist Herbert A. Simon to become a leading method to tackle today's human and technological needs (Friis Damm & Yu Siang, 2022).

Unlike in academic research, the goal is not always to validate preconceived hypotheses but to learn something new from each iteration (Brown, 2008). Bryan Lawson (1979) concludes from a series of experiments he performed with postgraduate architecture and science students that scientists are problem-focused problem-solvers, whereas designers are solution-focused.

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[2] (Grudin, 1992, p. 209)

Design thinking aims to efficiently identify and evaluate a suitable solution rather than spending excessive time analyzing the problem in depth (Cross, 1982). However, it is crucial to remember that the design process involves both quick prototyping and testing as well as slower and more deliberate creative and critical thinking. Striking a balance between these two approaches, rather than solely focusing on speed, is essential for a successful outcome. (Pontefract, 2018).

3.2.1 The four fundamental activities of design thinking

Design thinking in HCD requires an in-depth understanding of the target audience, their problems, goals, and frustrations. It requires creativity in finding various solutions to iteratively develop and improve prototypes based on findings from interaction with the target audience (Kelley & Littman, 2001). Hence, there are four fundamental activities in design thinking (D. A. Norman, 2002) that are repeated over and over:

1. Observation
2. Idea Generation
3. Prototyping
4. Testing

Throughout this project, I performed three iterations of the cycle in figure 4, yielding new insights into the requirements of an application to study navigation with an MR HMD and an improved prototype, which was tested for usability.
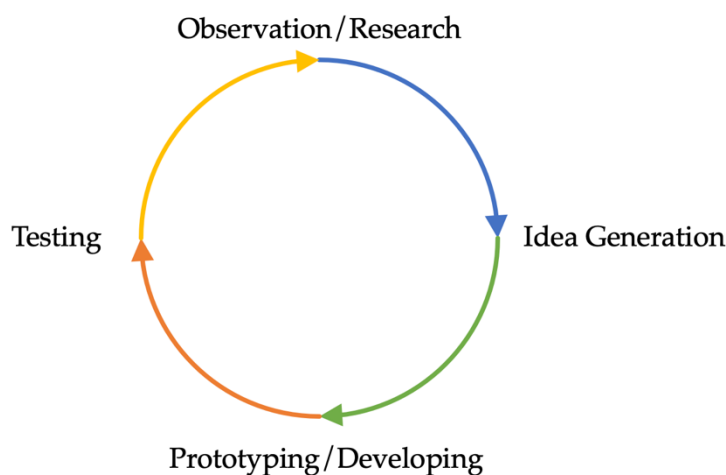
Figure 4: The four fundamental activities of design thinking according to Don Norman (2002)

Observation and Research

Each iteration of the design process begins with an observation and research phase, during which information about the intended users and their goals, motivations, and obstacles is collected (Buchanan, 1992). Moreover, it is critical to understand the context in which the application will be used. This information is commonly gathered through interviews, surveys, and text analysis. Based on

the results of this phase, a problem definition is developed, which serves as the foundation for the next iteration (B. Lawson, 1994).

Because I only had limited interactions with researchers studying navigation with MR interfaces, I used this project's observation and research phase to analyze and classify the publications of researchers who performed human navigation and wayfinding experiments. While the results are like a scientific literature review, due to the scope of this thesis, the search was much less structured and comprehensive. Moreover, I used this phase to evaluate existing, similar solutions and analyze whether they can be adapted or if certain aspects could be reused or inform the framework's design and compiled information on hardware and development tools to use. Finally, I also created detailed user personas for the target audience.

To conclude each research phase, I created a problem statement utilizing the data collected. It should serve as a roadmap to establish the objectives of the subsequent phases and set clear boundaries. This should ensure that the work is directed towards specific targets and stays on track.

Idea Generation

When there is a clear problem statement, the next step is to deduce concrete requirements for the application and generate potential solutions. According to Donald Norman (2002), there are three major rules to follow during this stage:

- Create and explore numerous ideas.
- Disregards potential constraints as even obviously "wrong" ideas can lead to creative insights.
- Question everything.

Most of the activities during this phase fall under the term "brainstorming" (D. A. Norman, 2002). However, as I was not working in a team throughout the project, there were no formal brainstorming sessions, and I performed many activities during this phase informally. Still, I used established methods from UI and UX design and requirements engineering to define and document my ideas. At the end of the idea generation phase, the goal is to have clearly defined functional requirements in the form of user stories and a clear understanding of non-functional requirements. Moreover, I used sketches to visualize ideas and possible solutions for the proposed requirements.

Prototyping

Much like in a scientific approach where a hypothesis is tested and either accepted or rejected, "*the only way to really know whether an idea is reasonable is to test it.*" (D. A. Norman, 2002, p. 227). A prototype enables designers to test and demonstrate their ideas (B. Lawson, 1994). There are multiple methods to create prototypes, which can be employed depending on the type and state of the project. In the early stages or for complex systems that cannot be built within a few days, prototypes can be simple sketches, small cardboard models, or even PowerPoint slides (D. A. Norman, 2002). At later

stages of the project lifecycle, prototypes should become more complex and interactive so that the concepts or ideas become more apparent and concrete.

At an early stage, the number of prototypes can be large but get smaller with more iterations and refinement (Lewrick, 2018). In the beginning, creating and testing all those ideas with low fidelity makes it possible to gather concrete ideas, disregard the ones that are not working, and improve upon those that seem to have potential. This enables designers to identify any problems with a design and address them before it is fully sketched out and developed (Kelley & Littman, 2001).

Even though modern technologies such as the Unity Game Engine have made working with AR and MR significantly easier, quickly creating simple AR/MR prototypes can still be challenging, especially for programming novices (MacIntyre et al., 2004). In the early stages of prototype development, I often used hand-drawn sketches to visualize some of my ideas. Furthermore, to create interactable, high-fidelity working prototypes for the HoloLens that I could test later, I used the Unity Game Engine in conjunction with additional toolkits and packages such as the Mixed Reality Toolkit (MRTK).

Testing

The goal of the testing phase is to get feedback and insights into the design and use of the prototypes created in the previous phase. According to Nielsen (1993b), it is the most central usability method because it provides a direct insight into how people use an interface and the exact problems they encounter.

Since the goal of the testing phases here is to help me continuously improve the proposed application, I will use formative testing methods. Nielsen (2012) argues that thinking aloud is the most valuable formative method in usability engineering. I will therefore perform a thinking-aloud test at the end of an iteration to evaluate the created solutions and determine changes and learnings for the next iteration. Moreover, in some cases where gathering test participants and preparing test tasks seemed excessive, I decided to perform heuristic evaluations according to the principles of Nielsen (1993a).

3.3 Methods of User Experience Design

Don Norman coined the term user experience design while he worked at Apple because he thought user interface and usability were too narrow (Merholz, 2008). UX, therefore, refers to a user's complete experience while interacting with an application, encompassing everything from the visual design to the flow of interaction and the system's documentation (Merholz, 2008). However, UX is a controversial term that is hard to define and refers more to a general concept rather than a specific practice or outcome (Buley, 2013). Therefore, I only use it to abstract the specific methods I used at different project stages and for different aspects of the application. I will use precise terms to refer to methods and outcomes wherever possible.

3.3.1 Distinction from User Interface Design

UX design is not to be confused with UI design; whereas UX is concerned with the whole user experience, UI design is only concerned with the visual aspects of an interface (D. Norman & Nielsen, 2012). It can therefore be considered as one aspect of UX that is undoubtedly crucial for commercial systems but may not be the first consideration in a low-resource context. As this thesis aims to create an intuitive and easy-to-use application, even for MR novices, the focus lies more on utility and usability instead of the visual design of any interface elements. This is not to say that I will completely ignore the UI design, but rather that the limited time and resources available for this project should be spent on other aspects of the design.

3.3.2 User Personas

In HCD and Design Thinking, knowing the target audience for which an application is developed is crucial. While user data could also be presented in the form of statistical figures, there is a possibility that these could be misinterpreted (Aquino & Filgueiras, 2005). Therefore, creating detailed descriptive representations of the target audience can help to more effectively and accurately determine requirements and features that meet the target audience's needs. One way to vividly represent the target audience is user personas, fictional characters that include detailed information about their behavior, motivations, and frustrations (Cooper, 2003).

While these personas can help visualize and communicate the target audience's characteristics, they do not replace researching the target audience and collecting tangible data about them (Matthews et al., 2012). User data, consequently, the basis for these fictional profiles can be created using several different methods (Cooper, 1999):

- **Interviews**: Talking directly to potential users and asking them about their preferences, motivations, and frustrations can give valuable insights. This can be done either in the form of one-on-one conversations, focus groups, or surveys.
- **Observation**: Observing people, naturally performing their tasks, can help to understand how they interact with an application and what they find important, useful, or frustrating. This can be done through field studies, contextual inquiries, or usability tests.
- **Data analysis**: Examining collected data such as user demographics, feedback, and behavioral patterns can help identify common user characteristics.

I used a combination of informal approaches to create user personas that represent the target audience of the application presented in this thesis. To understand the skills and motivations of GIScience researchers, I relied on my experience and observations during my time at the university as a student and teaching assistant. Moreover, I analyzed existing papers and had unstructured discussions with my Supervisors and Nicolas Morf (who performed an experiment that should be supported by the application presented here) to understand the goals and limitations of MR navigation research and, thus, the researchers performing it.

3.3.3 Methods of Requirements Engineering

The process of identifying, documenting, and managing the features of an application is usually referred to as requirements engineering (Kotonya & Sommerville, 1998). Defining requirements results from thorough research of the target audience, other stakeholders, and the context in which the application is used. However, it is important to note the difference between requirements engineering and design. Requirements describe the problem to be solved as precisely as possible, whereas the design determines how the problem is solved (Jackson, 1995). Determining requirements is critical in developing any application, as it improves and formalizes communication between designers and engineers.

I will use requirements engineering methods during the idea generation phase to formalize functional and non-functional requirements for the prototypes developed in the next phase. While I designed and developed the application presented in this thesis alone and do not necessarily require formal communication methods between designer and engineer (I perform both roles), it still makes sense to record the process so that it is later possible to retrace my steps and understand the reasoning behind decisions.

Functional Requirements

Functional requirements refer to specific tasks the target audience wants to perform when using the system. They are related to specific features and capabilities the system must have (Kotonya & Sommerville, 1998). An example of a functional requirement of a text editor would be that it must allow users to make text bold.

User Stories

will use user stories to describe the functional requirements of the application I. User stories describe features from the perspective of the target audience – in the context of this thesis, the user personas. They always follow the following structure (e.g., Leffingwell, 2011).

"As a [type of user], I want [some goal] so that [some reason]."

The user stories should fulfill the INVEST quality model (Wake, 2003). INVEST is an acronym of adjectives to describe a "good" user story:

- **I**ndependent: User stories should not conceptually overlap and can be implemented in any order.
- **N**egotiable: A story should capture the essence of a feature, not the details; they can be co-created when the feature is implemented.
- **V**aluable: A good story and the associated feature must be valuable to the target audience.
- **E**stimable: The time needed to complete a user story must be estimable so that it can be prioritized and ranked.
- **S**mall: I should not take too much time to implement a feature associated with a user story.

- **T**estable: A story must be clear enough so that it can be tested to determine whether an implementation fulfills its requirements.

Non-Functional Requirements

Non-functional requirements describe how a system should behave. Instead of referring to specific features (functional requirements), non-functional requirements are concerned with less tangible requirements, such as performance, security, usability (in a narrower context), and reliability. While functional requirements refer more to a system's utility, non-functional requirements often determine its usability in a broader context. Wherever necessary, I separately report on non-functional requirements in the form of specific targets.

3.4 Methods and Tools for Software Development

3.4.1 Architectural and Design Patterns

To ensure that the code of the application is readable and remains valuable over a long time, I will abide by well-known and defined software architecture and design patterns. For the final application, I used a Model-View-Controller (MVC) architecture (Gamma et al., 1995) and various design patterns, such as the abstract factory pattern, singleton, or observer pattern (Gamma et al., 1995). Moreover, I relied on traditional software development principles such as class inheritance, interfaces, and polymorphism.

3.4.2 Programming Tools

I used a combination of Unity and the MRTK as well as several packages developed for C# to develop the application for the HoloLens. Moreover, I used the JetBrains Rider IDE[3] and Microsoft Visual Studio[4] to develop and compile the project and deploy it to the HoloLens. I chose these developer tools for their convenience and relative simplicity compared to other tools, because they are widely used and thus are well documented, and because they have an active online community to get support if necessary.

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[3] https://www.jetbrains.com/rider/ (accessed: 13 November 2022)
[4] https://visualstudio.microsoft.com/de/ (accessed: 13 November 2022)

The Unity Game Engine

Unity[5] is a cross-platform game engine used to create 2D and 3D interactive experiences such as games, simulations, and visualizations. It supports Microsoft Windows, macOS, and various mobile platforms such as iOS and Android. Crucially, it also supports various AR and VR platforms, such as the Microsoft HoloLens. Crucially, it is free for non-commercial, personal use.

Unity is essentially a toolbox consisting of a drag-and-drop visual editor to create and design 3D worlds, a physics engine, support for various file formats, and many other convenient features. Thanks to the component-based architecture, it is possible to easily create so-called game objects (every button or character is a game object) and attach components that modify their appearance, behavior, sound, game logic, and any other aspect of their presence. These components can be created from scratch or extended with the C# programming language and a set of robust APIs that come packaged with Unity.

The C# Programming Language

C#[6] is an object-oriented programming language developed by Microsoft. It is part of the .NET framework[7], which includes an extensive collection of libraries for tasks such as threading, serialization, or logging.

The Mixed Reality Toolkit

The Mixed Reality Toolkit (MRTK)[8] is a collection of scripts for developing MR applications with different game engines, such as Unreal Engine or Unity, for various platforms. It adds a set of components, assets, features, and scripts to Unity that simplifies and accelerates the development of MR Applications for the Microsoft HoloLens. The MRTK is open source and available on GitHub[9].

Coordinates, positioning, and inside-out tracking

Unity uses a metric, cartesian, left-handed, y-up coordinate system (Mower, 2022). Such an absolute coordinate system works well for purely digital worlds because it allows developers to find a stable transform between any two objects in this digital world (Turner et al., 2022). Similarly, a GPS determines the position of a device and uses a digital representation of the world (i.e., a map) to determine relationships between the device and any other objects. Such an approach works well in

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[5] https://unity.com/developer-tools (accessed: 13 November 2022)
[6] https://learn.microsoft.com/de-de/dotnet/csharp/ (accessed: 13 November 2022)
[7] https://dotnet.microsoft.com/en-us/ (accessed: 13 November 2022)
[8] https://learn.microsoft.com/en-us/windows/mixed-reality/ (accessed: 13 November 2022)
[9] https://github.com/microsoft/MixedRealityToolkit-Unity (accessed: 13 November 2022)

situations where there is a digital model of the world, and the accuracy of the positioning is not critical (e.g., in outdoor Navigation).

However, in an indoor MR context, the accuracy of the positioning system is critical, and more often than not, there is no 3D model of the space available. Moreover, the HoloLens does not have a GPS because the accuracy does not suffice in most usage contexts. Yet, with the help of inside-out tracking, often implemented in the form of a SLAM algorithm, the HoloLens manages to simultaneously map the environment and determine the device's position with respect to that environment. It does so continuously while the user moves around the physical environment and updates its understanding of the world accordingly. Therefore, if the holograms were placed in a single rigid coordinate system, they would unavoidably drift either with respect to each other or the world (Turner et al., 2022).

"For example, the headset may currently believe two locations in the world to be 4 meters apart, and then later refine that understanding, learning that the locations are in fact 3.9 meters apart. If those holograms had initially been placed 4 meters apart in a single rigid coordinate system, one of them would then always appear 0.1 meters off from the real world."[10]

(Azure) Spatial Anchors

To solve the problem with the coordinate space mentioned above, the HoloLens design guidelines recommend using spatial anchors (Turner et al., 2022). Spatial anchors mark important points in the physical environment where the user has placed one or multiple holograms so that the system can recall those later. As the SLAM system learns more about the world, these spatial anchors can adjust their position in the real world based on each other. This prevents holograms from drifting over time (Turner et al., 2022).

On the other hand, Azure Spatial Anchors (ASA)[11] is a managed web service provided by Microsoft to store and share those spatial anchors over the web. ASAs use spatial mapping and computer vision techniques to remember and recall landmarks, much like humans. They are used primarily as digital markers to anchor digital holograms in the physical world so that they can later be retrieved by another person visiting the same place. As such, they can help to achieve object permanence for digital holograms. Moreover, they could be used as a localization technique in indoor environments or spaces with low GPS reception (e.g., Khan et al., 2022). While ASA is a commercial service, as of January 5th, 2023, it is free to use for academic purposes.

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[10] (Turner et al., 2022, Chapter 'Building a world-scale experience')
[11] https://learn.microsoft.com/en-us/azure/spatial-anchors/overview (accessed: 13 November 2022)

3.4.3 Hardware

While I explored different hardware as a platform to study MR Interfaces for Navigation, in the end, I decided to develop the application for the Microsoft HoloLens due to reasons outlined in section 4.1.1.

Microsoft HoloLens 2

The Microsoft HoloLens 2[12] is an MR HMD capable of displaying holographic content in the real world. The HoloLens 2 is an optical see-trough HMD which uses two semi-translucent laser-based waveguide stereoscopic displays in front of the eyes to display holograms. It uses an ambient light sensor, an IMU, and depth cameras to gather the data necessary to perform a SLAM-Algorithm that enables it to track the user's movement and understand the physical world around the user so that it can combine the physical and virtual worlds.

It uses a version of Windows 10 specifically developed for MR computing. It allows for voice interaction, gesture-based interaction, eye gaze interaction, or a combination thereof and can give visual or auditory feedback.

3.5 Methods of Usability Testing

As mentioned above, testing is a central aspect of the iterative design process. The goal of testing here is to observe how test participants – representing the target audience as closely as possible – interact with the application, any difficulties, confusion, and frustrations they might have and whether they use the application as imagined. Therefore, a qualitative approach can help find such usability issues and learn more about potential users at this stage. According to the ISO 9241 standard on the ergonomics of human-system interaction (ISO 9241: Ergonomics of Human-System Interaction, 2013), user interfaces need to be effective, efficient, and satisfying to use. However, these are hard to evaluate. Shneiderman et al. (2010) propose to evaluate user interfaces for the five main usability characteristics as proposed by Jakob Nielsen (1992).To test for most of those characteristics, thinking aloud is one of the most valuable methods (Nielsen, 2012).

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[12] https://www.microsoft.com/de-de/hololens (accessed 14 November 2022)

3.5.1 Thinking Aloud

"In a thinking aloud test, you ask test participants to use the system while continuously thinking out loud —
that is, simply verbalizing their thoughts as they move through the user interface."[13]

Thinking aloud was first proposed within cognitive psychology by Newell and Simon (1972) and later used to study how people learn text editors by Lewis (1982). Thinking aloud does not lend itself very well for performance measurements and benchmarking because of the somewhat artificial scenario – participants have to verbalize their thoughts in front of an experimenter – because participants may sometimes give inaccurate feedback, and because it is pretty time-consuming and thus hard to collect data with statistical validity (C. Lewis, 1982). However, its strength lies in the wealth of qualitative data one can collect with a relatively small number of test subjects (Nielsen, 1993b). Nielsen and Landauer (1993) have shown that thinking-aloud tests with five participants can yield enough insight to spot most interaction problems. In contrast, the results tend to become repetitive with more than nine participants.

For the think-aloud tests performed throughout this project, I relied on the descriptions of the process as outlined by Lewis (1982), Nielsen (1993b), and Norman (2002). I recruited six participants for each iteration in which I performed a think-aloud test. During each test, I let the HoloLens film the participant's point of view (POV), as I could not see what they saw during the test. Even though Nielsen (1993b) argues that filming a thinking-aloud test is unnecessary and notes usually suffice, I decided to record the tests from the participant's field of view so that I could complement my notes while seeing exactly what they saw.

Therefore, all participants signed a consent form (Appendix 8.1) agreeing to record their POV and Voice during the test. The participants were given a short questionnaire to determine basic demographics, their familiarity with MR HMDs, and the think-aloud method (Appendix 8.2). This was intended to somewhat control for participants already familiar with MR/VR interaction paradigms, specifically those of the HoloLens. Moreover, knowing their native language made me aware if people were performing the test in their second language – which I presume makes it harder to talk freely. Finally, knowing whether they have completed a thinking-aloud test before helps me ensure they understand the method and the task before the experiment starts.

To make participants more comfortable, I reiterated that the system is being tested and not them and that I do not have any personal attachment to the application being tested. They were then verbally introduced to the think-aloud method and shown two video examples of someone performing think-

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[13] (Nielsen, 2012, sec. 2)

aloud[14] [15]. To familiarize themselves with the technique, they were asked to search for the entry of Zaha Hadid in an architecture guide (Kempe et al., 2019) while thinking aloud.

After the test preparation, participants were fitted with the HoloLens and asked to perform an eye calibration. This served as a warm-up to familiarize themselves with some of the interaction principles of the HoloLens (e.g., how to press a button). They were then guided to the test area, a secluded section of the University Campus Irchel. As few people as possible needed to interfere during the test so that participants felt comfortable verbalizing their thoughts. I then illustrated the context in which they were using the application and afterward started the recording of the HoloLens.

Participants were never given a complete list of goals but separate tasks. They were asked to raise their hands as soon as they deemed the task done. I informed the participants of some features I considered to be not accessible by exploration (e.g., accessing the main menu by raising the hand). During the test, I continuously took notes and prompted them to verbalize their thoughts by giving them examples of what they could say every time they stopped talking for a while. Whenever a participant got stuck completely, I gave them hints to lead them back on the right track. At the end of the test, I stopped the recording and helped them to take off the HoloLens. On the way back to the starting location, I asked them for feedback, input, and attitudes towards the application and the HoloLens in general in a short unstructured interview.

3.5.2 Heuristics and Heuristic Evaluation

Heuristics are general principles to evaluate user interfaces. Nielsen's 10 Usability Heuristics for User Interface Design (Nielsen & Molich, 1990b) and Schneiderman's Eight Golden Rules of Interface Design (Shneiderman et al., 2010) are probably the most famous and commonly used. These include, among others:

- **Provide feedback:** The user should always be informed about the system's state.
- **Natural dialogues**: Dialogues and prompts should not show irrelevant information but only what is needed at the moment.
- **Speak the user's language**: Information should be expressed clearly in phrases familiar to the user rather than in system-oriented terms.
- **Minimize the user's memory load:** Users should not have to remember things over a long period.
- **Consistency**: Terms and concepts should be applied consistently.

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[14] https://www.youtube.com/watch?v=BwpPIiBK0cA (accessed: 12. December 2022)
[15] https://www.nngroup.com/articles/thinking-aloud-demo-video/ (accessed: 12. December 2022)

- **Permit easy reversal of actions**: Actions should be easily reversible so that the system is more explorable, and errors are less consequential.

Nielsen and Molich (1990a) have shown that heuristic evaluations of three to five people can successfully find most usability problems. Since I can only perform those evaluations alone, and because it is currently unclear how and whether they apply in AR/MR interfaces (Derby & Chaparro, 2021), I will only use heuristic evaluation sparingly for relatively simple parts of the interface.

3.5.3 Utility Testing

I did not use formal methods to prove the application's utility as there were currently no researchers utilizing the application to perform an MR navigation experiment. Therefore, I will use the discussion to prove the application's utility.

4 Results

Since I used an iterative process to continuously develop and improve "LandMarkAR", the result section is organized to represent the iterations through which I achieved the current state of the application. For each of the three iterations, I describe the results of each activity within the design thinking framework. At the end of each iteration, I discuss the implications of the results of the steps for the next iteration.

4.1 Iteration 1

4.1.1 Requirements Research

As mentioned in section 3.1, knowledge about the types of research questions, the tools researchers use for human navigation experiments, and an understanding of how researchers use them to answer different questions is crucial for developing "LandMarkAR". Therefore, building on the discussion of potential experiments in section 2.5.3, I present and discuss possible tools to perform these studies as they were used in the literature. Moreover, as outlined in section 3.1.2, to design usable and useful software, it is crucial to understand the skills and requirements of the potential users.

Research Tools

The tools used to perform an experiment are central to the experiment design. It was essential to have an overview of existing solutions to perform such experiments to understand whether existing solutions could satisfy the requirements of a research tool to perform navigation experiments in MR. Moreover, if some tools partially cover the requirements, whether they can be adapted to a degree where they fulfill most requirements.

As shown in the section 2.5.1, there are two approaches with four different implementations to perform MR wayfinding experiments, each with its advantages and drawbacks. On the one hand, there are studies conducted in a 3D environment in a laboratory. The 3D environment can be presented in a CAVE (Cave Automatic Virtual Environment – usually a room-sized, stereoscopic 3D projections system) (GIVA, 2022) or, more recently, with VR goggles. Participants typically locomote through the environment using a joystick, a keyboard, and a mouse or by walking on an omnidirectional treadmill (e.g., Ruddle, Volkova and Bülthoff, 2013). On the other hand, studies can be performed "in the wild" in an uncontrolled setting. Here, researchers use a smartphone with a camera or an HMD to embed virtual information directly in the physical environment.

Existing tools to perform laboratory experiments

I have found two notable research toolboxes that would potentially enable the study of MR for pedestrian navigation systems. "OpenMaze" was developed by Alsbury-Nealy et al. (2022). "OpenMaze" is a toolbox for the Unity Game Engine where "*all experiments are defined using human-readable configuration files*" (Alsbury-Nealy et al., 2022, p. 1374), enabling even researchers with no prior coding experience to define and conduct experiments. Moreover, there is "Landmarks", which was developed by Starrett et al. (2021). "*Landmarks combines the ease of building drag-and-drop experiments using no code, with the flexibility of allowing users to modify existing aspects, create new content*" (Starrett et al., 2021, p. 1046). Like "OpenMaze", "Landmarks "was created with and for the Unity Game Engine. Thanks to the flexibility of Unity, experiments designed with either of these tools could then be presented to participants either in a CAVE lab or with VR goggles.

Existing tools to perform "in-the-wild "experiments

I have decided to discard smartphone-based AR navigation systems early on because they do not provide any functionality over HMDs while being less immersive for the user. Unlike a goggle, the smartphone acts, much like binoculars, as a window to AR and requires the user's focus which presumably requires a similar cognitive load to traditional map-based navigation systems (Dong et al., 2021). The alternative to smartphone-based AR are HMDs. While there are multiple MR-enabled HMDs, such as the Magic Leap 2[16] or the Varjo XR-3[17], I have decided to only consider the Microsoft HoloLens as a viable option due to the more readily available developer tools and documentation. Of the four papers that used the Microsoft HoloLens (Section 2.5.1), three have developed their solutions either using native code (Bågling, 2017) or the Unity Game Engine in conjunction with the MRTK (B. Liu et al., 2021, 2022) and one used the Microsoft 3D Viewer[18] (Morf, 2022) to perform the experiment.

Target Audience
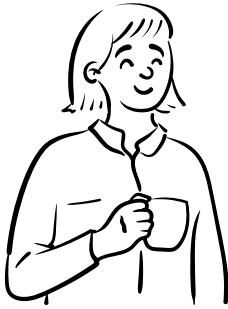
Understanding and knowing the target audience (i.e., the users) plays a vital role in HCD and helps to define the requirements better and design a useful application. User personas are a great way to represent the target audience of an application and will be used here to formalize the characteristics of potential users. The target group of this framework are researchers rather than end-users of a potential MR navigation system – they would be potential participants in an experiment created by a researcher.

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[16] https://www.magicleap.com/en-us/
[17] https://varjo.com/products/xr-3/
[18] https://apps.microsoft.com/store/detail/3dviewer/9NBLGGH42THS?hl=de-ch&gl=ch

Field (2014) described that the experiment's primary stakeholders are the Experimenter and the Participant. Likewise, they are the most important stakeholders for the tool described in this thesis. Even though the experimenter will mainly interact with the interface described in this thesis, it is crucial not to forget the experiment participant, as they will interact with an experiment based on what the experimenter has created with the tool described here.

Riley 32

"The Scientist"

Biography

- Has Studied Geography with a focus on GIScience.
- Has a background in (spatial) statistics.
- Passionate about psychology and human behavior.

Skills

- Has considerable experience with experiment design and statistical methods.
- Has experience with scripting languages such as python or javascript.
- Is familiar with different data collection, and analysis methods.
- Capacity to learn new programming tools with detailed instructions and online tutorials.

Goals

- Understand how potential users react to mixed reality interfaces – perform user and task centered studies.
- Design elaborate experiments to understand the effects of mixed reality on user behavior, emotion, cognitive load and so forth.
- Get statistically significant results.

Frustrations

- Long coding sessions/Spending too much time on the computer.
- Having to debug code over long periods of time.
- Writing code without architectural guidelines.
- Performing qualitative Research.

Figure 5: Card for the scientist persona interested in performing user and task centered studies.

Personas

Researchers

Harper 24

"The Designer"

Biography

- Has at some point in their career studied UI and UX design.
- Has a background in economics.
- Passionate about architecture, design and 3D Animation.

Skills

- Has considerable experience in web design and with 3D graphics.
- Knows prototyping software such as Figma or 3D graphics suites such as blender.
- Tech-oriented, learns unfamiliar GUIs through exploration.
- Has great interviewing skill and considerable experience in conductive qualitative research.

Goals

- Explore how and where mixed reality interfaces could replace traditional desktop or mobile interfaces – perform interface and design centered studies
- Understand how the design of desktop/ mobile applications could inform the design of mixed reality applications and how the two differ

Frustrations

- Technical difficulties and buggy software
- Using ambiguous User Interfaces
- Writing code that goes beyond defining the visual appearance of a user interface.
- Quantitative Research

Figure 6: Card for the designer persona interested in performing interface and design centered studies

The primary users of "LandMarkAR" will be researchers in the field of GIScience, more specifically in Geovisualization, Navigation, and Spatial Learning. However, because geography and GIScience is an interdisciplinary field, there will be researchers with different foci in their research, different skill sets,

and consequently, different demands for the app's functionality. To do the different backgrounds, skills, and needs of the potential users justice, I have created three user personas, all majoring in Geovisualization either as master's or Ph.D. students. These personas are based on people I have encountered at university. They are the result of my experience during various projects in Software Engineering and GIScience and my time as a teaching assistant in GIScience and Remote Sensing.

Erin 27

"The Techie"

Biography

- Has a background in software engineering.
- Passionate about geography – especially localization and navigation techniques.
- Develops their own Apps and Programs in their free-time.

Skills

- Has considerable experience in object-oriented software development.
- Knows multiple programming languages such as python or java.
- Is familiar with software design and architecture patterns.
- Capacity to learn unfamiliar software development environments through exploration.

Goals

- Explore the technical possibilities with the HoloLens – improve the application and add functionality
- Explore and implement a large range of functionality.
- Make an app run as smoothly as possible.
- Write extensible and easily readable code.

Frustrations

- Undocumented Code.
- Unstructured or Spaghetti Code.
- Spending to much time conceptualizing ideas instead of creating a prototype and testing them.

Figure 7: Card for the techie persona interested in improving the application and adding new features.

However, it is essential to note that they are entirely fictional and do not represent a specific person I have met or talked to.

The cards (Figures 5, 6, 7) represent the three personas. The visual representations were created with the "open peeps" illustration library (Stanley, 2022). They differ in their background, skill set, motivations, and frustrations. Two personas (the "scientist" (Figure 5) and "designer" (Figure 6) personas) are the core users of the application and represent researchers that will use the app mostly without writing any additional code. The features of the application will be tailored to their needs. Their main goal is to perform experiments to assess the suitability of MR for navigation. However, their interests in what types or classes (Section 2.5.2) of experiments differ. While the "scientist" persona is mainly interested in performing user and task-centered studies, the "designer" persona is interested in performing interface and design-centered studies.

Moreover, their methodical approach differs; while the "scientist" persona usually prefers a quantitative approach, the "designer" persona prefers a qualitative approach. Of course, the fact that the personas, classes of studies, and research approach match so well is a deliberate decision and does likely not represent reality in all cases. However, it makes the design process easier, as features can be tailored to a specific persona instead of a vague conceptualization.

In addition to the more traditional researchers, the "techie" persona (Figure 7) represents a superuser whose goal will be to contribute to the development of the application by defining new features and writing code. While the features of the application are the primary concern during the development of the application, it is also crucial to consider future contributors and make contributing as easy as possible. Ideally, the application presented in this thesis provides functionality that enables people, with similar skill sets to all the personas mentioned here, to create MR navigation experiments.

Experiment participants

As mentioned above, experiment participants constitute a significant stakeholder as they will spend a lot of time with the application during the experiment. Even though the features I am designing are not likely to be used directly by the participants, it is still important to consider the ethical concerns surrounding the use of MR HMDs (Steele et al., 2020). The application should not promote any unethical behavior by the researchers and should always protect the privacy and autonomy of the participants. While participants may have additional goals and frustrations, those are mainly the researcher's concerns and are related to the experiment design. Should I realize that participants are more affected by some features than I anticipate at this stage, I would revisit the participant persona in a later iteration.

Problem Statement

During this first research phase, I found that no existing applications have a complete set of functionalities to perform wayfinding and spatial learning experiments in MR. Even though the 3D Viewer Application for the HoloLens provides a basic set of functionalities that enables researchers to conduct experiments (e.g., Morf, 2022), it lacks many functions enabling more in-depth experiments.

Therefore, it became apparent that I would develop a framework more geared explicitly toward indoor navigation and spatial learning experiments with MR interfaces.

I have focused on three main aspects of the framework: the user, the hardware, and potential research questions. It has become clear that potential users cannot be expected to have advanced programming skills, which is why the framework must have a graphical user interface. However, due to the breadth of possible, novel research questions, the tool must be flexible, expandable, and give researchers much control over test variables. Therefore, there are ideally different interaction levels for users with different skills, so the framework can grow and adapt to different user needs. Moreover, while it would be possible to study MR interfaces in a VR environment, the problems associated with VR studies (e.g., Starrett et al., 2021) and the need for more "in-the-wild" studies (Merino et al., 2020) arguably make MR HMDs the ideal tool for the framework. Therefore, the goal for the next phase is to create ideas for an MR application on the Microsoft HoloLens that is flexible and expandable but also easy to use.

4.1.2 Idea Generation

As mentioned in the last section, one central aspect of a navigation study is how to present route instructions. Researchers, therefore, must be able to create route instructions and present them to the experiment participant. Building a fully-fledged navigation system would require a lot of groundwork, like surveying the environment and creating a navigation tree (e.g., Bågling, 2017). As this would go beyond the scope of this thesis, I decided that I would have to build a system where researchers can create experiments more akin to so-called "Wizard of Oz" experiments. This method can mimic powerful systems, like an MR Indoor Navigation system before they are built (D. A. Norman, 2002).

Figure 8: Person resizing a digital chair with the Microsoft 3D Viewer (Microsoft, 2022)

Route sketches on maps visualized in MR are a compelling use case, especially in contexts where users must have both hands free for other tasks, such as firefighters in a building with low visibility (i.e., task-based studies). However, since this approach does not differ significantly from using a digital map on a device (e.g., attached to the wrist) and because it would again require a digital model or a map of the study area and a rather complex localization technique to visualize the experiment participant's position, I have decided to focus the application on turn-by-turn route instructions positioned as holograms directly in the environment. This approach also has the advantage that researchers can place digital landmarks or highlight physical landmarks (i.e., any hologram of their choice) in addition to the route instructions.

Researchers should therefore be able to place route instructions directly in the environment. At first glance, there are two approaches to that. Users may use a graphical user interface (GUI) on a desktop or some configuration file, for example, in "OpenMaze" (Alsbury-Nealy et al., 2022), to determine the style and location of 3D holograms. Alternatively, there could be a Direct Manipulation Interface on the HoloLens where users can place, resize, and style 3D objects directly in the environment, for example, the 3D Viewer used by Morf (2022). The second approach has the advantage that the digital model of the study area can be built while the researcher is placing the holograms. In contrast, the first approach again would require a virtual model of the natural world with a mechanism for the HoloLens to determine the position and orientation of itself and the wearer within the real world and the data model.

Therefore, I decided to follow and test a direct manipulation approach for the first iteration. Morf (2022) has shown that the Microsoft 3D Viewer on the Microsoft HoloLens can be used to create a navigation experiment. However, it comes with several limitations (e.g., participants accidentally moved Holograms during the experiment, changed the setup, no integrated data collection methods, no mechanism to access to position of holograms from any other device, etc.).

While I could have used the 3D Viewer to test the suitability of this approach to creating experiments, I also wanted to explore possible programming tools for the "techie" persona (Figure 8). I decided to implement a lightweight prototype using these technologies to explore Unity and the MRTK as possible solutions for the "techie" persona.

Interaction Levels

The application should be able to support incremental levels of technical skills for increasingly complex use cases, to do the three personas created during the last phase justice. These interaction levels are similar to those used by Starrett et al. (2021) in their implementation of "Landmarks". However, in contrast to "Landmarks", which does not have a GUI but relies on the Unity Editor, the interaction at the software level should start with a GUI on the Microsoft HoloLens for researchers who cannot go through deployment from Unity to HoloLens (table 4).

Table 4: Different interaction levels for the user personas considered in this thesis.

ID	Software Level	Associated User Persona	Hardware Level
A)	GUI – position Holograms to perform simple experiments.	"The Designer"	Wear the HoloLens to prepare an Experiment
B)	Unity Editor – add simple functionality by adding scripts to Game Objects or add new 3D Shapes.	"The Scientist"	Connect the HoloLens to a laptop, deploy the application directly from Unity, then wear the HoloLens to prepare and experiment.
C)	C# – add core functionality directly in Unity, by creating scripts and everything necessary.	"The Techie"	Develop new features on Laptop, deploy the application as a development version from Unity, use the HoloLens to test new features

Requirements – User Stories

For the first iteration, I will mainly consider the lowest interaction level (i.e., the GUI on the Microsoft HoloLens). Based on the research and discussion above, the application's functional requirements were documented as user stories (Appendix 8.4.1). Table 5 includes a summary of those stories.

Table 5: Summary of the User Stories determining the functional requirements of iteration 1

Story Nr.	Story Title
I.I	Placing Holograms
I.II	Moving, rotating, resizing Holograms
I.III	Locking Holograms
I.IV	Save Experiment
I.V	Load Experiment
I.VI	Undo/Redo Command

User Interface Elements

The core idea of the application is that researchers can place holograms at a position of their choice and move, rotate, and resize them so that they correspond to their requirements. These holograms correspond to so-called prefabs in Unity.

*"Unity's Prefab system allows you to create, configure, and store a GameObject
complete with all its components, property values, and child GameObjects as a reusable Asset. The Prefab Asset
acts as a template from which you can create new Prefab instances in the Scene"[19]*

To place a hologram, there needs to be a prefab menu where users can select a prefab with a shape, appearance, and behavior of their choice and position directly in the physical environment.

Prefab Menu

The prefab menu could look like the menu in the 3D Viewer (Figure 10). There, users can navigate
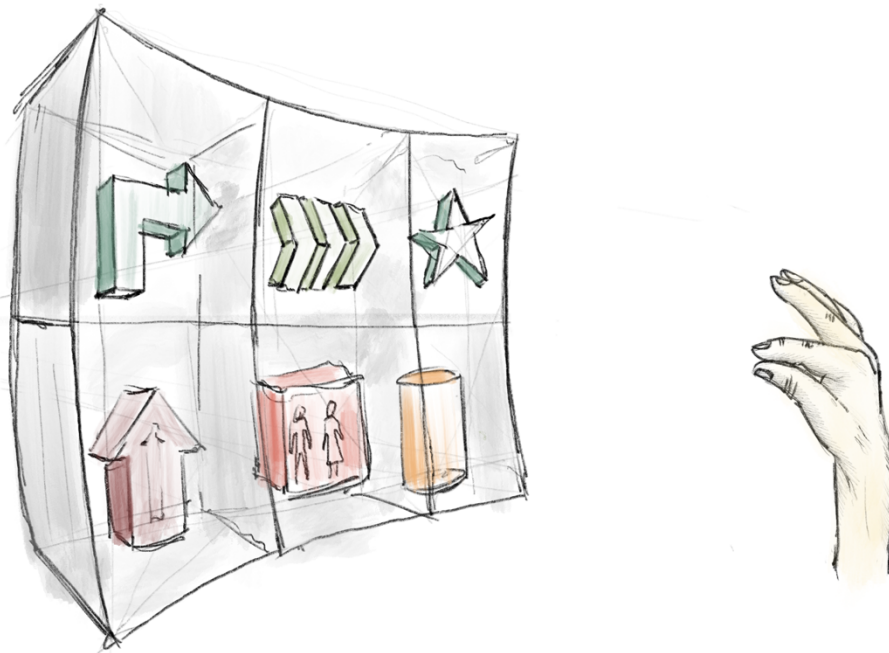
Figure 9: Sketch of a prefab menu where users can just grab an object and place it in the physical environment.

through a menu on a slate like a WIMP-Interface on a desktop computer or a smartphone and click on a 3D object they want to place using their physical hands. The object then appears right in front of

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[19] (Unity Manual, 2022, sec. 1)

them. I also sketched an alternative solution where users would grab a 3D item similar to how people grab an item from a produce aisle or cupboard (Figure 9).

Independently of the design of the prefab menu, there is the question of how to access it. One solution would be a voice command; however, this would require the user to know the command, which is not ideal. Moreover, other items, such as locking the holograms (User story I.III) or saving and loading created holograms (User story I.IV, I.V.), also require an interface. Therefore, it makes sense to access all these functionalities from one single point of entry (Heuristic 4: Design Dialogues to yield closure (Shneiderman et al., 2010)).

Figure 10: The menu to select 3D objects in the Microsoft 3D Viewer and a hologram of a hamburger selected from the menu and placed next to it.

Main Menu

To have that single point of entry to access essential functions such as saving an experiment and accessing a menu to place holograms or lock holograms, I decided that researchers would require some sort of main menu. However, the main menu must be able to be hidden, at least during an experiment, so that participants do not accidentally access it. Moreover, hiding the main menu when not in use may also be helpful to researchers because it does not block the visibility of other elements.

To access the main menu, I considered two solutions, either via voice command or by raising the hand with the palm facing toward the user. Both solutions are elegant because the main menu is hidden to experiment participants but accessible to informed researchers. For this first iteration, I decided to follow the Hand Menu approach, which is gracefully supported by the MRTK. Should I find any usability issues with this approach, I would pivot to a voice-based approach at a later stage.

Figure 11 shows sketches of two approaches to designing a hand menu with the MRTK. In the first approach, menu items are placed right above the fingers so they can be pressed with the other hand.
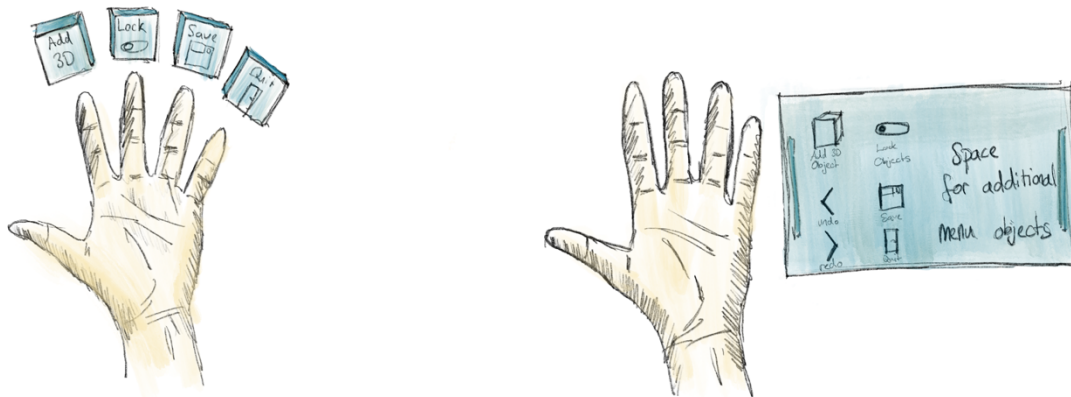
Figure 11: Sketch of two possibilities to visualize the main menu when the user is raising their hand.

In the second approach, the menu items are arranged on a slate that could potentially be grabbed and placed elsewhere for convenience. While the first approach would look "cool", the second approach probably makes more sense from a usability standpoint. The menu items are not limited to four, they can be logically grouped, and the slate keeps them together. Even if the slate is grabbed and placed elsewhere, the menu items stay in a consistent relationship with each other (Heuristic 4: Consistency (Nielsen, 1993a)).

Hologram Interaction

Finally, after a researcher has placed a hologram, they will want to move it, resize it and rotate it, and crucially prevent that from accidentally happening. The MRTK offers scripts and assets to implement these interactions, like in the 3D Viewer application on the HoloLens. A wireframe with handles can be displayed around the object to signify that the user can interact with the hologram. Ideally, these would vanish as soon as an object is locked so that it is evident that the object cannot be changed.

To edit a hologram, users can grab an object by pinching their thumb and index finger and move and rotate holograms much like they would when interacting with physical objects. Moreover, should the object be too far away, the MRTK offers a pointer with a ray so that they can again grab the object by pinching their thumb and index finger and then move the object, similar to how they would move a phone on an elastic selfie stick. To resize the object, users can either grab the hologram with both hands and bring them closer together (like a pinch-to-zoom gesture to a multi-touch interface) or one of the corners of the wireframe around the object (like how one would resize a photo in photoshop).

4.1.3 Prototype Development[20]

Based on the designs from the last phase, I built the first lightweight prototype using Unity and the MRTK. In addition to the designs created in the previous phase, I will try to follow the MRTK interaction paradigms (Bury et al., 2022) as closely as possible since it is highly likely that these were already tested for usability at some stage. The prototype should enable the most basic interactions needed for the application framework such that I can test the designs from the last phase and find out whether HoloLens and MRTK interaction paradigms apply in the context of this thesis.

During this first iteration, I intended to mainly approach functionality for interaction level A) (Table 4) and satisfy requirements for the "Designer" and "Scientist" persona. To build the first prototype as quickly as possible, I did not spend too much time on software architecture and extensibility – two major requirements for the "Techie" persona – because I wanted to test the designs mentioned above as quickly as possible so that I would be able to rethink my approach should they head into a completely wrong direction.

Included functionality

The first prototype included GUI elements for all the stories mentioned in the user stories section of this iteration. However, to keep the prototype light and simple, there are only implementations for stories I.I, I.II, I.III (Creating, Moving/Rotating/Resizing Holograms and locking Holograms), there was no save and load mechanism, as building a save system was no focus of the first iteration. However, it was earmarked to be implemented in Iteration 2.

Description of the UI

As mentioned above, the three central aspects of the UI of the prototype are:

- The main menu (i.e., a hand menu)
- The prefabs menu (to select holograms)
- Interaction with holograms and the locking mechanism

For this UI, any other aspects were discarded, meaning that there is no way for a user to save any holograms that they might have placed. Moreover, there is no way to delete holograms or change their appearance. Finally, a user starts directly in an environment, and there is no home menu where users can create or select different MR environments to enter.

Main Menu

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[20] To get access to the repository containing the source code, please get in touch with Tumasch Reichenbacher (tumasch.reichenbacher@geo.uzh.ch) of the GIVA group.

The main menu is the main entry point to the application's user interface. Since the app is used by both researchers (in the setup phase of the experiment) and participants (during the experiment), one particular requirement for the main menu was that it is hidden and can only be opened by a researcher. While there were multiple solutions to this (e.g., a voice command), the MRTK hand menu

Figure 12: The hand menu (i.e., main menu) in action.

offers an elegant solution. The user can access the main menu and its functionality by raising their hand with their palm facing towards themselves (Figure 12). The user can lock the menu in space by grabbing the right or left dotted lines with the other hand. By raising their hand, the menu will again show up next to the palm. While this solution does not strictly prevent experiment participants from accessing the main menu, I assume it is hidden enough not to be accidentally opened. The usability testing phase will show whether the hand menu is an excellent solution to access the main menu.

While a convenient way for researchers to access the main menu is crucial, the contents are even more important. The requirements for this prototype show that there needs to be functionality to place a hologram, save and load an experiment, lock holograms, and undo and redo an action. Initially, access to all these functionalities is placed in the main menu (Figure 12). While only the locking mechanism and the access to the hologram menu are functional in this prototype, the others are still placed in the menu to see how users react to them during the usability test.

The functionality to lock and unlock all holograms (User story I.III) for the experiment phase is implemented as a simple toggle button in the main menu. By pressing "Research mode", all holograms are locked and cannot be moved, resized, or rotated until unlocked.

Prefabs Menu

The goal of user story I.I is to place 3D Holograms in an indoor environment. To do so, the user needs a dedicated menu to select a 3D Object or prefab (As they are called in Unity) and place it in the real world. The term Prefabs refers to prefabricated 3D objects that can be placed in the real world without defining their properties. However, at a later stage, it might make sense for users to be able to change certain properties such as hue, value, or even texture.
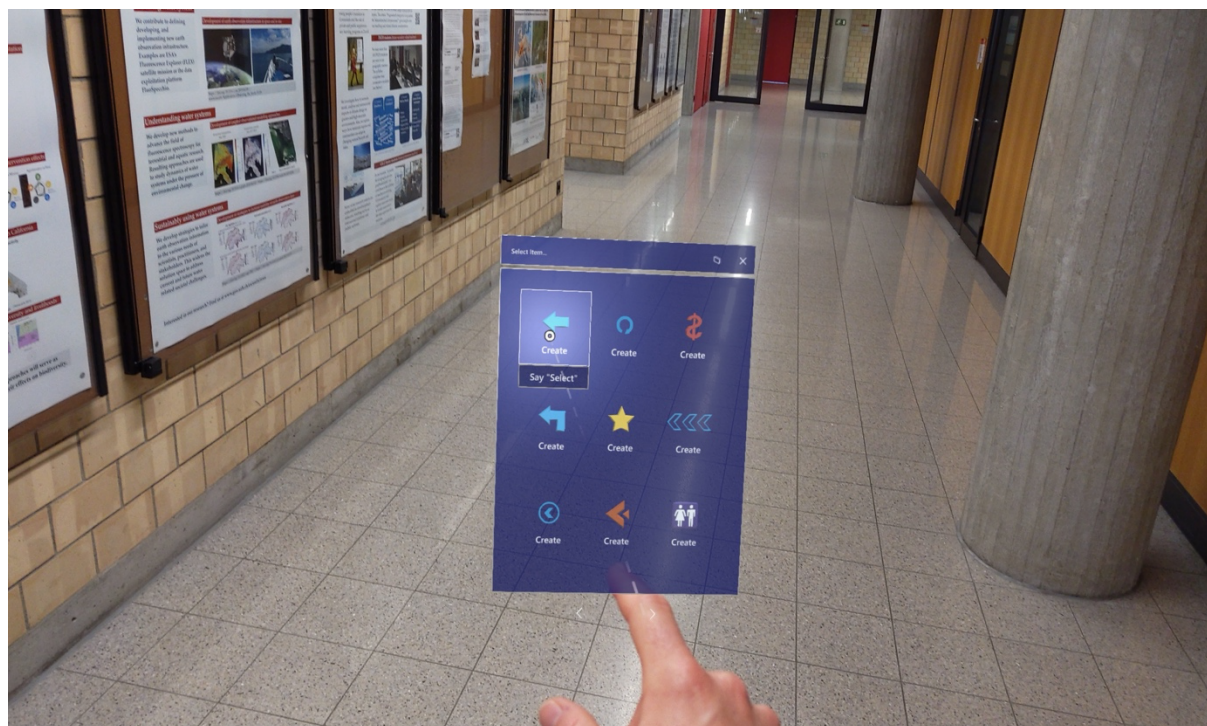
Figure 13: The prefabs menu of the first prototype in action

The Prefabs Menu can be accessed by pressing the "Open Prefabs Menu" button in the main menu (Figure 12). Pressing the button in the main menu will open the Prefabs menu in a new window right in front of the user (Figure 13). To close the menu, the users can press the "x" in the top right corner, much like on a regular desktop. Moreover, they can toggle whether the menu should follow them or stay in place by pressing the second button in the top right corner (two overlaying rectangles). They can then scroll through the available objects and select whichever object they would like to place. Users can press one of the objects, like a button, to place an object. The object will then appear right in front of them (Figure 14).

While I think an implementation akin to the one in figure 9, where users just grab an object from the virtual rack, could have been intuitive and exciting, I decided to implement a more straightforward approach based on the assumption that people are already familiar with WIMP-interfaces and therefore able to transfer that familiarity to the MR context. Should the results of the usability test show that the decision was not ideal, I can always go back and implement another approach to test.

Hologram Interaction

After placing a hologram, users can move, rotate, and resize it to their liking (User story I.II). To move a Hologram, users can grab an object in the center by tapping their thumb and index finger together (Figure 14, right) and then move it by moving their hand to the desired position. To rotate a hologram,

Figure 14: Interactions with 3D holograms placed in the real world.

they can use the same gesture to grab an object and then rotate it by changing the orientation of their wrist. Finally, to resize an object, users can grab and pull one or two of the corners of the wireframe surrounding the object again by pressing the thumb and index finger together (Figure 14, left). Users can then resize the object by moving their hand inside (to make it smaller) or outside (to make it larger) of the object, similar to the pinching gesture used to zoom in or out on a mobile phone.

Locking Mechanism

To perform an experiment, researchers must be able to prevent Holograms from being accidentally moved by an experiment subject (User story I.III). Researchers can activate the research mode to lock
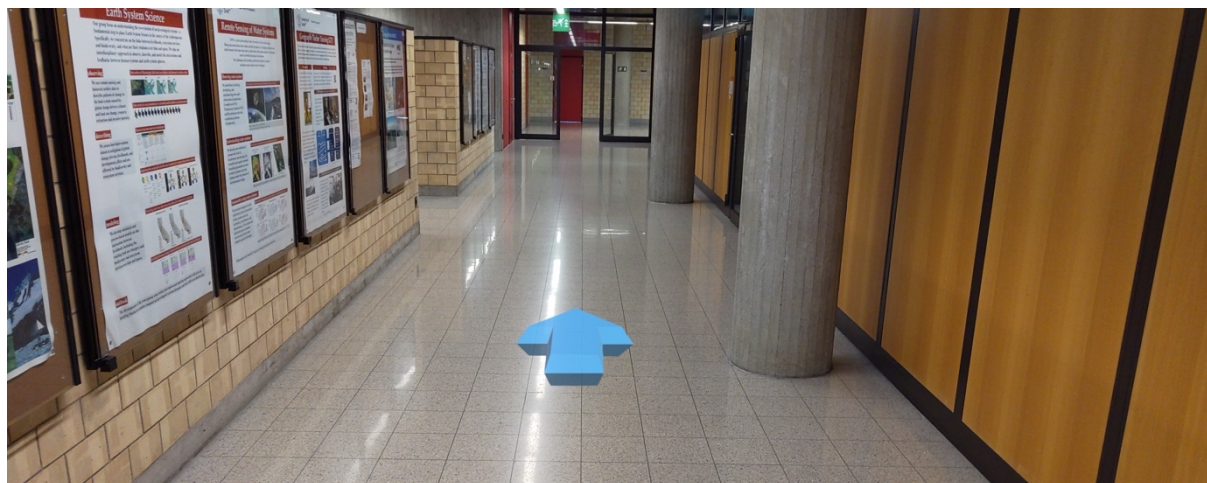
Figure 15: The locking mechanism in action (signified by the missing wireframes around the hologram)

Holograms by using the toggle button in the hand menu (Figure 12). To signify that the Holograms are locked, the wireframes around the Hologram are removed (Figure 15), which has the additional advantage that test subjects can only see the Hologram and not the wireframes around it.

4.1.4 Usability testing

In the final phase of the first iteration, I qualitatively tested the interface's usability. I used the think-aloud method to evaluate the prototype's interface (Section 3.5.1). At this stage, I decided not to formally discuss the utility of the prototype, as it is quite similar to the 3D Viewer. By performing an experiment with the 3D Viewer, Morf (2022) has already shown the utility of such an interface for navigation experiments.

Questionnaire Results

Before the usability test, the participants completed a short questionnaire to gather basic information about previous experiences with MR and VR. For this first iteration, I had six participants, of which three were female, and three were male. None of the participants has performed a thinking-aloud before. While four performed the usability test in their native language (German), two performed it in their second language (English). All the participants have used a VR or MR HMD before. However, only three have used the Microsoft HoloLens before.

Test Area and Tasks

The usability test was performed between different aisles of lockers at the Irchel Campus of the University of Zurich. The area was chosen because it offers a layout akin to a labyrinth and because it is usually quiet during lecture hours (Figure 16). The participants were led to the starting point of the experiment and given information about the context – building a route description to the nearest bathroom using holograms of their choice.

Figure 16: Image of the test area for the first think-aloud usability test at the Irchel Campus. Locker aisles that serve as a "labyrinth" and a physical sign highlighting the closest bathroom.

Before the start of the test, the participants were informed that they could access the main menu (i.e., the hand menu) (Figure 12) by raising their hand with their palm facing them because that is hard to

find out without prior knowledge. After I started the recording on the HoloLens, the participants were given the first task and asked to raise their hand as soon as they were done. Appendix 8.3.1 shows the complete list of tasks. Once the participants were done with the last task, I stopped the recording and helped them to take off the HoloLens. At the end of the test, I also tried to start a discussion about their experience to possibly learn more.

Test Outcome

Participants took, on average, 17 minutes to complete all the tasks, with a standard deviation of about 6.5 minutes, a minimum time of 5.5 minutes, and a maximum time of 24.5 minutes. For some participants, completing the tasks took a lot longer than expected, while some were exceptionally fast. On the one hand, the large difference in completion time stems from the fact that some participants tried to explore more and took longer to arrange objects to their liking. On the other hand, some of the difference probably also stems from the fact that one participant already had a lot of experience using the HoloLens. In contrast, others had never used it before. These findings indicate that the interface does have a learning curve, but the interaction paradigms of the MRTK seem to work quite well after the users are familiar.

Although none of the participants directly commented on it, the hand menu (i.e., the main menu) worked well as a practical entry point to the application's functionality. All the participants managed to open, see, and use the menu on the first try. However, this may be a result of them being told how to use it. Still, it indicates that people can quickly learn how to use the hand menu.

It became immediately apparent that the names of menu items were not ideal. Neither the prefabs menu nor the research mode effectively describes what they do. Through trial and error and elimination of obviously wrong commands for the given task, participants could determine the correct button to click when trying to lock all the items or access the menu to place 3D objects. The terms also break Nielsen and Molich's (Nielsen & Molich, 1990b) 2nd Usability Heuristic that the terminology in UIs should be based on users' language and not some system-specific terms.

The participants usually still managed to access the prefabs menu (i.e., the hologram menu). While clicking on a Button with an object to create it worked well, the menu got in the way of participants quite often. Most participants did not realize that the menu could be closed or placed in a specific location. They also did not actively recognize that the menu automatically followed them. However, they implicitly appreciated that it did so because none of the participants returned to look for the menu where they last saw it. However, because the menu followed the participants and no one figured out that the top right buttons could be used to either close it or fix it in a particular position, some participants accidentally created holograms. Moreover, it probably seems unnecessary that each of the buttons to create a hologram is accompanied by the word create as one participant exclaimed: "Create, create, create, create, [hahaha], everywhere create." (Translated from the German original) (Figure 13).

As mentioned above, placing holograms worked exceptionally well. All the participants immediately saw the hologram once they clicked the button to create one as it popped up right in front of them.

The hologram also seemed to have a good size, to begin with, not too large or too small for users to immediately spot it and explore the available interactions. Moreover, the wireframes and handles are great signifiers to indicate that the object can be interacted with. Even though some of the participants took some time to figure out all the degrees of freedom (move, rotate, resize) to adjust an object, all of them eventually figured out all of them.

Finally, some participants were also unsure what the "Save Experiment" and "Load Experiment" buttons exactly do. They were informed that the functionality was not implemented and asked what they would expect the buttons to do. One participant mentioned that they would expect the system to save automatically. Others noted that they were unsure whether loading an experiment would delete all the holograms they had just placed. None of the participants was interested in the undo and redo commands.

4.1.5 Discussion and implications for future Iterations

The first usability showed that the overall direct manipulation approach, where the users can place digital objects directly into the physical environment and interact with them similarly to how they would interact with physical items, makes sense in the given context. While the direct hand interaction with the holograms took some time to get accustomed to for most test participants, after a while, they felt natural and were referred to as being "fun", "cool", or just "wow". Here it helps that the MRTK supports multiple interaction types for the same actions right out of the box.

Moreover, it has become clear that the names of the menu items are not intuitively understandable. The term research mode could make sense if it would not only lock items but also do other things like, for example, start data collection. However, if it is only there to lock items in place, the button should probably just be called lock items. On the other hand, Prefabs Menu comes from the Unity specific term "prefabs". This terminology could make sense for the "Techie" persona but does not make sense for any other personas. The button should probably be called "3D Objects" or "Holograms".

Additionally, some participants had problems with the menu to place 3D Objects. A lot of the time, it obstructed a clear view of the hologram after it was created and prevented unobstructed interaction with the hologram. While one option would be just to hide the menu as soon as an object was instantiated, I will probably have to redesign the process of placing objects at some point. While I still like the idea of grabbing an object from a virtual "shelf" (Figure 9), it feels like this approach could have similar issues to the one tested here.

Overall, this first iteration has shown that the initial overall approach to the interaction with holograms works quite well – most probably because it was already extensively tested and refined by the developers of the MRTK. Similarly, the "Scientist" and "Designer" user personas represent the target audience quite well, and the current approach does fulfill their most basic requirements quite well. However, so far, the prototype does not meet any of the requirements of the "Techie" persona, as the code is messy in many cases and does not follow any architectural design patterns. This should not be a big problem at this stage, as the prototype will likely change significantly over the subsequent iterations.

At this stage, the application is still quite general and could potentially be used to answer many of the research questions mentioned in the background. However, there are currently no methods for data collection except the possibility of recording the POV of the wearer of the HoloLens. While it is desired that the application offers a general toolbox, the current prototype does not yet provide a lot of utility, especially since the 3D Viewer offers similar functionality in a more stable application.

4.2 Iteration 2

4.2.1 Requirements Research

One central feature the 3D Viewer does not offer is the ability to create different environments containing different holograms at varying positions. In other words, digital objects, like physical objects, remain in place until they are moved. The application will potentially be used by multiple people simultaneously, performing different experiments, requiring the ability to place different holograms in the same place. They will therefore need functionality to save the state of their MR environment, let others create another environment, and then go back to the previous environment so that they can use it with different participants.

While I already created user stories to define those requirements in the last iteration, they will probably need refinement. Some participants mentioned the save system because two buttons in the hand menu were teasing the functionality in the main menu. It has become apparent from the last usability tests that there has to be some system that saves newly created holograms automatically and communicates that to the user accordingly.

Physical and digital world(s)

Objects have permanence in the physical world as long as no external force is acting upon them. This permanence results from the physical laws governing reality and matter's inherent properties. For example, a chair stays in the same position until moved and remains a chair until destroyed. The same chair will also always be made from oak.
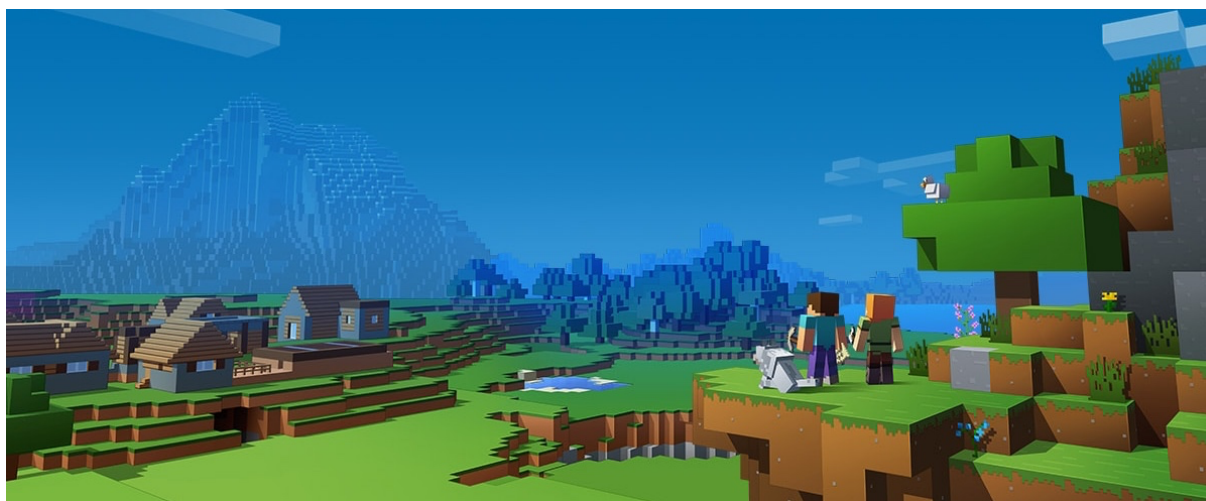
Figure 17: Scene from Minecraft; a virtual sandbox simulation game where players can create their own worlds using mostly cubical-shaped elements. (Minecraft, 2022)

Computers can be used to simulate and visualize such a world. However, there, the permanence of objects relies on the memory of the computer. Of course, the bits representing those objects are physical and act much like the chair mentioned above. However, if those bits are used to store the properties of a chair, which are then used to draw such a chair on screen, the resulting representation

of a chair may behave quite differently from the physical chair mentioned above. While the computer can simulate physical laws so that the digital chair behaves similarly to its physical twin, the digital chair can change its appearance and size or vanish in seconds by changing the bits that hold the information about the chair.

Minecraft[21] (Figure 17) is a virtual sandbox game that represents the relationship between digital and physical worlds quite well. While the game follows the laws that govern the physical world to some degree, players can "spawn" new objects within seconds and use them to create as many worlds as they like. As long as the digital and physical worlds are strictly separated, these differences do not result in conflict. However, in MR, this is no longer the case. Holograms can be created within milliseconds and placed in the real world. Therefore, to deal with these problems, some concepts of the digital world (e.g., from Minecraft) can be used and adapted to the physical world.

Problem Statement

During the second research phase, I found that users will need to be able to create independent environments. These environments are similar to layers in a GIS. Therefore, much like Minecraft, users can create and move digital objects in different environments containing different combinations of digital objects. In other words, when using the HoloLens, there is one physical world, but possibly many virtual worlds that can be chosen to be shown.

To retain their work, it is, therefore, necessary to create a system to create different environments (in this context, they could probably be called experiments), keeping track of the digital object so that the progress can be saved and loaded at a later stage. At this stage, it is not entirely clear whether the term environment or experiment is better to refer to a stored collection of holograms.

There is no integrated system in unity to automatically store and load relevant data when starting and stopping an application. In the first step, developers ought to decide which data to retain over multiple sessions and how they want to store or serialize those data and objects. Based on the previous prototype, the save system for this application will have to be able to create experiments that retain the following attributes of each hologram:

- The position
- The size
- The rotation
- Basic Appearance Information

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[21] https://www.minecraft.net/de-de

As is apparent above, the save system should retain similar information to a file containing geographic point data. Thus, it could potentially be inspired by file structures for geographic point data.

4.2.2 Idea Generation

There are two aspects of creating the save system for the application. The first aspect is concerned with the UX design and the communication of the environment logic (i.e., how can users understand when they can expect to see the elements they placed in a previous session). The first aspect is essential for users interacting on interaction level A) (Section 4.1.2). The second aspect is more technical and concerned with software architecture (i.e., how can the attributes of a hologram be saved so that they can be retrieved in a later session). This aspect is vital for users interacting on interaction level C).

Requirements – User Stories

In the first iteration, the requirements for saving an experiment/environment were rudimentarily captured in Stories I.IV and I.V. However, the complexity of the problem statement of this iteration requires them to be revisited and complemented. These new and improved user stories can be found in Appendix 8.4.2. Table 6 summarizes those stories.

Table 6: Summary of the User Stories determining the functional requirements of iteration 2

Story Nr.	Story Title
II.I	Create New Experiment
II.II	Name Experiment
II.III	Save Experiment
II.IV	Load Experiment
II.V	Quit Experiment
II.VI	Object permanence

In addition to the essential user stories above, there are user stories that correspond more with interaction level B). These do not have a high priority at this stage but could be valuable in the future. They would also probably require a more complex save system. A summary of these additional stories can be found in table 7 and the stories can be found in Appendix 8.4.2.

Table 7: Summary of additional User Stories determining possible functional requirements of iteration 2 with a low priority

Story Nr.	Story Title
II.VII	Reuse existing holograms
II.VIII	Query the location of holograms
II.IX	Query participant path

Non-functional requirements

Since the additional user stories above would probably require a more complex save system, a central non-functional requirement is that the save system is easily extensible. Extensibility corresponds to interaction level C) (Section 4.1.2). In other words, people corresponding to the "Techie" persona should be able to adapt the save system to more complex requirements. Moreover, the loading times of the system (i.e., opening the application, loading an experiment, and all the holograms) should remain manageable for a researcher.

UX Design

The save system could be designed akin to a start screen on a desktop application. Users are guided through creating a new experiment or loading an existing one. In addition to the start screen, the users will need functionality to save and quit (go back to the start screen) the experiment while they are creating it (e.g., some buttons in the hand menu).
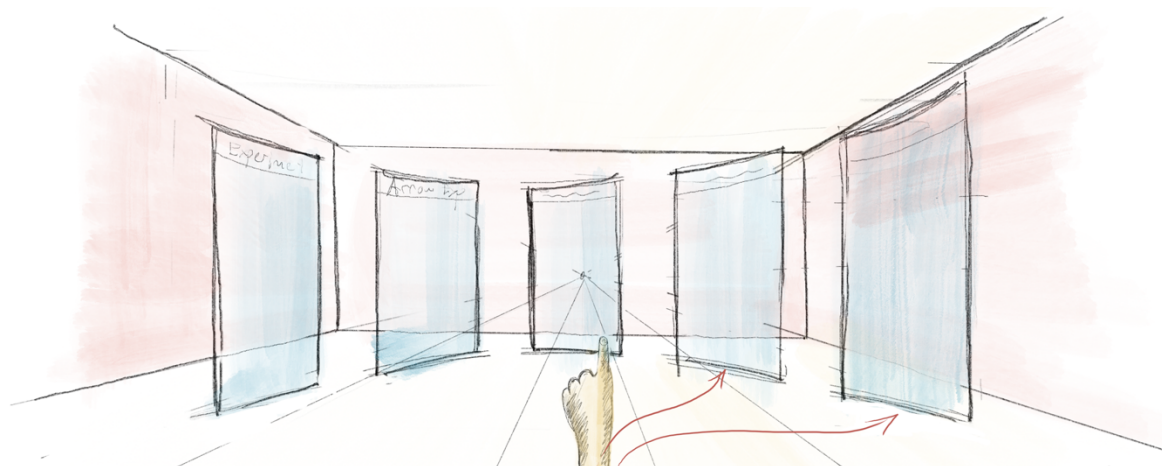
Figure 18: Sketch of a home menu where users walk through a digital door to open an experiment.

My first idea for implementing such a start screen was to have a design quite different from traditional start screens. Instead of having digital slates where users click through a dialogue, like on a desktop, there are virtual doors through which users walk to open an experiment (Figure 18). For each

experiment, there will be a door; each door is labeled with the experiment name and shows a preview of the used holograms. A new experiment could be created by walking through a door marked "New Experiment". Then the user would be prompted to type the name of the experiment.

The second idea is to use MRTK slates to simulate a screen-based interface and create a traditional dialogue. I have sketched two similar options for such a dialogue. The first option is a screen that
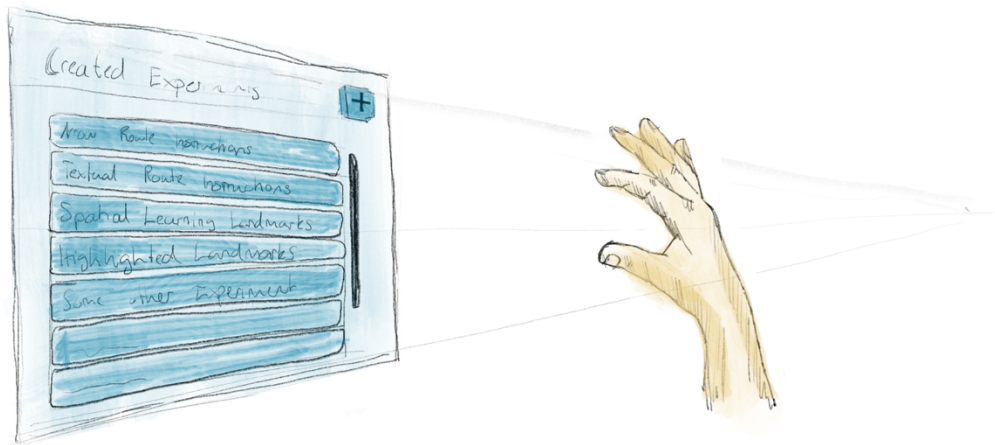
Figure 19: Sketch of a holographic dialogue showing a list of experiments which can be opened by physically clicking on a list element.

shows a list of all the experiments where users just click on a list element to open the experiment (Figure 19). To create a new experiment, there is a plus button in the top right corner. The plus button would open a new dialogue where users can type the name of the new experiment with a holographic keyboard (Figure 20, right).

Alternatively, there is a simple start screen, where the user only has two options – either pressing a button to create a new experiment or opening an existing experiment (Figure 20). When the user
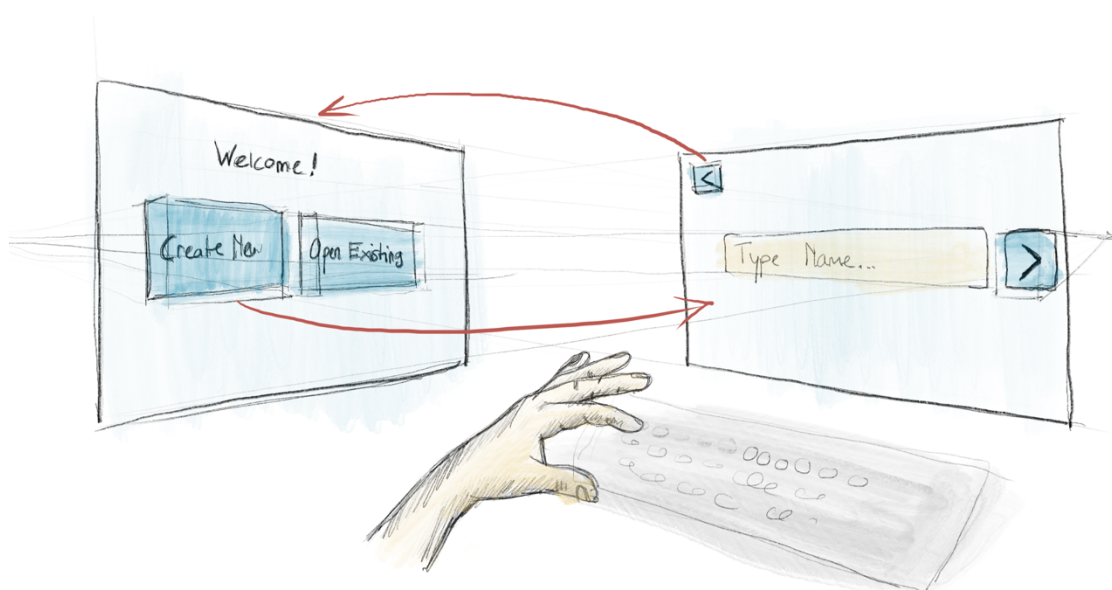
Figure 20: Sketch of two holographic dialogues – One start screen with two options and a screen to type an experiment name with a holographic keyboard.

wants to create a new experiment, another simple dialogue is shown where they can either create a new experiment by typing a name and clicking the create button or go back to the start screen. When the user clicks on open existing, a slate showing a list of all existing experiments is shown (Figure 19), where the user can either open an experiment by clicking on a list item or go back to the start screen.

Technical considerations

The simplest solution to building a save system would be just to store the unity coordinates of each hologram and recall those later. However, because the unity origin of the coordinates is arbitrary for each session and due to the problems associated with inside-out tracking (Section 3.4.3), the system will have to rely on environmental data captured by the HoloLens.

Building a custom SLAM system with persistence functionality would go beyond the scope of this thesis. Therefore, I will use the Microsoft Spatial Anchors as a basis for the save system, even though their implementation details, beyond the API, are unknown. In other words, they are a black box. Should holograms drift too much compared to physical objects during usability tests, I will have to reconsider their usage.

Saving holograms

There are several approaches to saving holograms. The simplest one would be to store the IDs of local spatial anchors and attributes of the associated hologram. This approach would require the HoloLens to store all the spatial anchors, which can affect performance. Should they be deleted (which can be done through the HoloLens settings), the position of the associated hologram is lost.

Alternatively, the spatial anchors and attributes of a hologram could be stored on azure using the ASAs service. Then, the system would only have to keep track of ASA-IDs locally. Such an approach would prevent the spatial anchors from being accidentally deleted and has the additional advantage that the same experiment could be viewed from multiple devices simultaneously. However, this approach would require using the ASA service, which always requires an internet connection and could cause costs in the future.

Finally, the Microsoft World Locking Tools[22] leverage spatial anchors to create a stable, reproducible coordinate system during inside-out tracking. With the World Locking Tools, it would be possible to store coordinates and attributes of holograms like point data stored in a GIS. This approach has the advantage that holograms are independent of spatial anchors. Their coordinates could be geocoded and used in any GIS or mapping application. Moreover, the system would have consistent

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[22] https://learn.microsoft.com/en-us/mixed-reality/world-locking-tools/documentation/concepts
(accessed: 10.10.2022)

information on the user's position over time, enabling it to track them within the world-locked coordinate system.

4.2.3 Prototype Development[23]

Based on the designs from the last phase, I built a new prototype with Unity and the MRTK from scratch. I decided to discard the code from the first iteration because it did not follow any specific architecture and was messy. The main goal of the second prototype was to get familiar with spatial anchors and decide which approach to saving holograms I should take.

During this iteration, I was mainly concerned with functionality for interaction levels B) and C) (Table 4) as the save system has a direct influence on data collection and extendibility of the application, which mainly concerns the "Techie" and "Scientist" persona. Obviously, the UI of the save system also affects the "Designer" persona and should represent a "One physical world, many virtual worlds" concept so that it is easily understandable.

Included functionality

The prototype created during the second iteration is not an advancement of the first prototype but rather a separate implementation to explore and test one central aspect of the application – the save system. The second prototype included the GUI for the save system, as mentioned in the user stories section of this iteration. Moreover, it also contains a technical solution to store holograms and experiments (a collection of holograms), so they can be retrieved later. I have implemented functionality satisfying the user stories II.I to II.VI. The additional user stories were not implemented at this stage because of their technical complexity, but they point to possible routes for future iterations.

Description of the UI

When opening the application, the user is greeted by a simple dialogue (Figure 21), which is always oriented towards the user and stays in the center of their field of view. This ensures that the user sees the dialogue and knows the possible actions. This first dialogue contains only two options; create a new experiment or open an existing one. To select one of the options, users can either "Air Tap" or physically press the button with their index finger.

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[23] To get access to the repository containing the source code, please get in touch with Tumasch Reichenbacher (tumasch.reichenbacher@geo.uzh.ch) of the GIVA group.

When a user selects "New Experiment", the home dialogue is replaced by a dialogue containing a text field, a button to create the experiment, and a button to go back to the home menu (Figure 22). A holographic keyboard automatically pops up so the user can enter a name for the experiment. Once done, they can press enter or the "x" on the top right of the keyboard to hide it. After the user clicks

Figure 21: The home dialogue the user sees when they start the application or leave an experiment.

"create", the empty experiment is loaded, and they can start to place holograms. The name of the experiment serves as a unique identifier. If a user tries to use a name already used, they are prompted with an error message that instructs them to use another name.

Figure 22: Dialogue to create a new experiment with the holographic keyboard to type a name.

When the user selects "Load Experiment", a new dialogue containing a list of all previously created experiments shows up (Figure 23). Users can open one of the experiments by "Air Tapping" or

clicking on one of the list items. Alternatively, they can return to the home menu by clicking the return button in the top left corner. There is also an option to delete all the experiments at once for development purposes. At a later stage, it should be possible to delete each experiment

Figure 23: Dialogue showing a list of existing experiments. Each element can be selected to open the respective experiment.

independently.

I decided to implement a more traditional interface than the idea outlined in the section 4.2.2 phase, where a user walks through a digital portal. It is closer to conventional interface design on desktop and mobile computers. Users are more familiar with such an interface and, therefore, more likely to understand immediately what they can do.

Summary of Implementation Details

I decided to create an implementation of the save system using ASAs. They have the advantage that the system must only persist the spatial anchors' ids. Therefore, an experiment is essentially just a list of ASA-IDs that can be stored as a ".json" file on the device. The location and appearance information is stored in a single place on the web. If there is a requirement at some point that multiple people should be able to see the same experiment while they all wear a HoloLens, all that is necessary would be a simple web server that can store and share these ". json" files. Moreover, the "Scientist" persona could potentially compile experiments from already placed holograms through a relatively simple web UI that could be built.

While ASAs have the caveat that they always require a stable internet connection, they have fewer unwanted side effects than local spatial anchors. They cannot be deleted directly from the HoloLens and can be easily shared across devices. Moreover, the attributes of holograms are shared online as well. At this stage, the system does not store any coordinates online but relies solely on visual features

to recognize an existing hologram. The World Locking Tools could be easily integrated later by a researcher akin to the "Techie" persona should they be required.

4.2.4 Testing

As the UI created in this iteration is relatively simple, I decided not to test it with actual users. Instead, I performed a heuristic evaluation of the UI as described by Nielsen (1994) (Appendix 8.5.1).

Test Results

As part of the heuristic evaluation, I evaluated each screen for Nielsen's ten usability heuristics (Nielsen & Molich, 1990b). In addition, I also assessed whether the slates are always visible or whether there is a chance that a user overlooks them.

I am still unsure at this stage whether the term experiment best describes what users are creating or whether "environment" or "digital world" would be better suited. However, this can only be tested with actual users. Moreover, I found that while the slates always follow the user's gaze so they cannot be overlooked, they could also block the sight of critical physical features which users could miss and fall down a stair, for example.

Furthermore, the heuristic evaluation also showed that simply relying on the experiment's name might not be enough for users to remember. They might need additional information, such as a preview image, to know which experiment to open. Moreover, I found that the buttons to select an existing experiment (Figure 23) might be a bit small to hit them efficiently. In combination with the fact that there is no way for the user to know which experiment they have currently opened, this could lead to slips where users accidentally open and edit the wrong experiment.

Finally, while I have already started to document the code to be readable and understandable, there is no user guide available at this stage. Even though there is currently no need for it, at some point, a short guide outlining the most important features, such as the hand menu developed in iteration one, could make sense.

4.2.5 Discussion and implications for future Iterations

Unlike in the first iteration, in the second iteration, both the user interface and technical aspects of the save system were equally important. The technical implementation determined the user interface to some degree. Moreover, it impacted the potential for automatic data collection using the framework, such as the ability to track and query for the path walked by an experiment participant.

Technical Implementation

The implementation of the save system at this stage works well enough to store and recall holograms like the 3D Viewer. It has additional advantages, such as creating different experiments showing different holograms in the same place. Moreover, holograms are saved online and cannot accidentally be deleted by flushing the local hologram store of the HoloLens.

However, saving holograms online requires a constant internet connection for the application to work. While most of the University Irchel Campus has a wireless local area network (WLAN) connection, it still could prove challenging in areas with low or unavailable connectivity. Nonetheless, the advantages outweigh the disadvantages as this system allows for better extension and fewer unwanted side effects.

With the World Locking Tools, the current system could be supplemented with a rigid, reproducible, and, if necessary, pre-established coordinate system for each experiment or even the whole Irchel Campus. The save system could potentially also be enhanced by a survey mode which leverages the functionality of the world locking tools and the HoloLens' inside-out tracing to map the physical environment into a coordinate system which could then be used as the basis for experiments. Then, given they are geocoded accordingly, the holograms could also be represented as point data on any map.

In conclusion, the current state of the save system will suffice for the final prototype presented later in this thesis. However, there is room for improvement, and thanks to its design, other contributors can easily expand it should it be required.

UI Design

The heuristic evaluation showed that I could expect the UI for the save system to work quite well. Although I liked the idea of the virtual portals through which a user can walk to enter another digital environment, the current system will probably work better as it is more familiar to the target audience. I think the portals are an excellent metaphor for merging virtual and physical worlds (Heuristic two of Nielsen's (1994a) ten usability heuristics). However, they have some caveats that would make them harder to design. For example, it is unclear how to communicate that users have to walk through the doors or how to prevent doors from ending up directly in front of a wall. To have consistency and follow the design of familiar interfaces (Heuristic four of Nielsen's (1994a) ten usability heuristics) probably makes more sense in the given context.

Thanks to the heuristic evaluation, I still found some minor issues with the interface. On the one hand, I will probably have to increase the distance between the slates and the user so they can still see their physical environment. This change is essential to prevent accidents. On the other hand, the problems with the size of the buttons can be easily solved by making them a bit larger. To determine an appropriate size, some flavor of Fitts' law (Fitts, 1954) could provide guidance.

Finally, I will probably have to test some elements with actual users. While the keyboard seems good enough to type the name of an experiment, I expect it to become annoying if users type more than a couple of words. At this stage, no UI element signifies to the user that an object or an environment is saved. Even though the system saves objects automatically as soon as they are created, users can not be expected to know that. There probably should be some form of feedback in the next prototype, especially if the spatial anchor cannot be saved in the cloud for some reason. Understanding user expectations of the save system should be part of the next think-aloud test.

As mentioned above, the prototype of the second iteration is not an enhancement of the first prototype but rather an implementation of another crucial aspect of the application. Therefore, the main goal for

the third iteration will be to bring these two prototypes and the learnings from the first two iterations into one final prototype. Moreover, there will have to be additional features to add value over the Microsoft 3D Viewer so that it is not a simple replica.

4.3 Iteration 3

4.3.1 Requirements Research

One central task of the third iteration is consolidating the learnings and designs from iterations one and two into a third prototype. While a consolidated prototype based on the user stories from the last iterations adds value over the 3D Viewer, Morf (2022) also found limitations upon which the next prototype should improve.

Limitations of the HoloLens and the 3D Viewer

The next prototype should aim to improve upon Morf (2022) 's issues with the occlusion of holograms by walls. Moreover, there might be solutions to remedy the limited FOV of the HoloLens through software and leverage the built-in eye-tracking to collect more participant data, as proposed by Morf (2022). Finally, like in the 3D Viewer, there will probably have to be some interface for users to add their own 3D models as it is impossible to cover all shapes of holograms users might expect the application to include.

Visual Variables and their Significance in Mapping

The visualization style of map elements and landmarks in mobile pedestrian navigation systems influences the users' behavior and spatial learning (e.g., Fuest et al., 2021; Kapaj, Lanini-Maggi and Fabrikant, 2021). It is, therefore, likely that this will also be the case in MR pedestrian navigation systems. Consequently, the ability to adjust the visual representation of holograms in real-time will significantly improve the application's usability.

Bertin's visual variables (Bertin, 1983) are a set of graphical design elements used to visually communicate information. They have been continually expanded and have become canonical in geographic information visualization. It, therefore, makes sense that users can change the visual representation across these dimensions.

"The visual variables describe the graphic dimensions across which a map or other visualization can be varied to encode information."[24]

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[24] (Roth, 2017, p. 1)

According to Roth (2017, pp. 3-4), the following variables derived from variables as discussed by Bertin (1983), MacEachren (1995), and MacEachren et al. (2012), can be used to encode information in a map symbol:

- **Location**: "*The position of a map symbol relative to a coordinate reference frame.*"
- **Size**: "*The amount of space occupied by a map symbol.*"
- **Shape**: "*Describes the outline/visual form of the map symbol.*"
- **Orientation**: "*The rotation of the map symbol as compared to the normal orientation.*"
- **Color Hue**: "*The dominant wavelength of the electromagnetic spectrum of the map symbol.*"
- **Color Value**: "*The relative amount of energy emitted from the map symbol.*"
- **Texture**: "*The coarseness of the fill pattern within the map symbol.*"
- **Color Saturation**: "*The spectral peakedness of a map symbol.*"
- **Arrangement**: "*The layout of graphic marks constituting a map symbol.*"
- **Crispness**: "*Describes the sharpness of the boundary of the map symbol.*"
- **Resolution**: "*Describes the spatial precision at which the map symbol is displayed.*"
- **Transparency**: "*describes the amount of graphic blending between a map symbol and the background or underlying map symbol.*"

In addition to these static variables originally intended for print media, DiBiase et al. (1992) and MacEachren (1995) developed dynamic variables to visualize spatiotemporal phenomena. These additional variables were developed to formalize the role of animation in interactive maps. The variables they developed are intended for the visualization of data on geographic phenomena and, thus, do not perfectly translate to the context of this thesis. However, they show that animation and movement are essential for mapping and geographic information visualization.

Problem Statement

The main goal of the third iteration will be to consolidate the learnings from the last two iterations into a final application prototype. However, the requirements research phase of this iteration has shown that to satisfy the needs of researchers and to improve upon existing solutions like the 3D Viewer; the application will also need additional functionality.

The appearance and design of map symbols are central aspects of cartography. Likewise, the ability to change the appearance of holograms (i.e., map symbols in the augmented territory) is crucial for the application. While users could already change some visual variables such as position, orientation, or size in the first prototype, the new prototype will need an interface to change other variables of a hologram as well.

Moreover, if time allows, there should be additional functionality to collect research variables relevant to specific research questions automatically. While the list of potential variables is vast, leveraging the HoloLens' eye-tracker to learn more about a participant's visual attention during an experiment, as was proposed by Morf (2022) or done in some of the experiments presented section 2.5.1, could be a low-hanging fruit.

4.3.2 Idea Generation

Like in the second iteration, in addition to UX and UI design, technical design aspects such as software architecture play an important role during this iteration. Since one of the goals of this project is to build an application that can be extended in the future, requirements for the "Techie" persona, which corresponds to interaction level C) as discussed in iteration one, gain importance. Furthermore, I can transfer many designs from the first prototype into the new one. However, it will be crucial to integrate new functionality seamlessly and apply learnings from the first iteration.

Requirements – User Stories

Based on the research and discussion above, the application's functional requirements were documented as user stories (Appendix 8.4.3). Table 8 is a summary of those stories.

Table 8: Summary of the User Stories determining the functional requirements of iteration 3.

III.I	3D hologram shape
III.II	Upload shape
III.III	Add shape in Unity
III.IV	Lock/Unlock Proportions
III.V	Change Color
III.VI	Change Opacity
III.VII	Animate hologram
III.VIII	3D Text as hologram
III.IX	Orient text to user
III.X	Understanding the save mechanism
III.XI	Display eye gaze

Non-functional requirements

In addition to the functional requirements mentioned above, I realized that recording the FOV while using the HoloLens requires considerable computing power. However, in many experiments, it might be necessary to do precisely that. Therefore, the application has to run efficiently enough so that researcher can still record the participant's FOV during the experiment.

UX Design

While I can adopt the hand menu (i.e., the main menu) from the first iteration with only minor adjustments, the prefabs (or hologram menu as it probably should be called) will need major changes. Since users should be able to edit the appearance of holograms according to visual variables of cartography, add 3D text to an environment and upload their own 3D objects as holograms, I will have to rethink how users place and edit holograms.

Main Menu

 The main menu will not change dramatically. Yet, the third iteration is an opportunity to revamp it to become tidier. Instead of showing all menu items at once like in the first prototype (Figure 24, left), it could make sense to nest them in a menu that shows specific items grouped whenever the user needs to access them (Figure 24, right). Reducing the number of options users can choose from in a single moment could make the UI more explorable and easier to use. Moreover, it might make it easier to expand later because the submenus can grow instead of the whole menu.
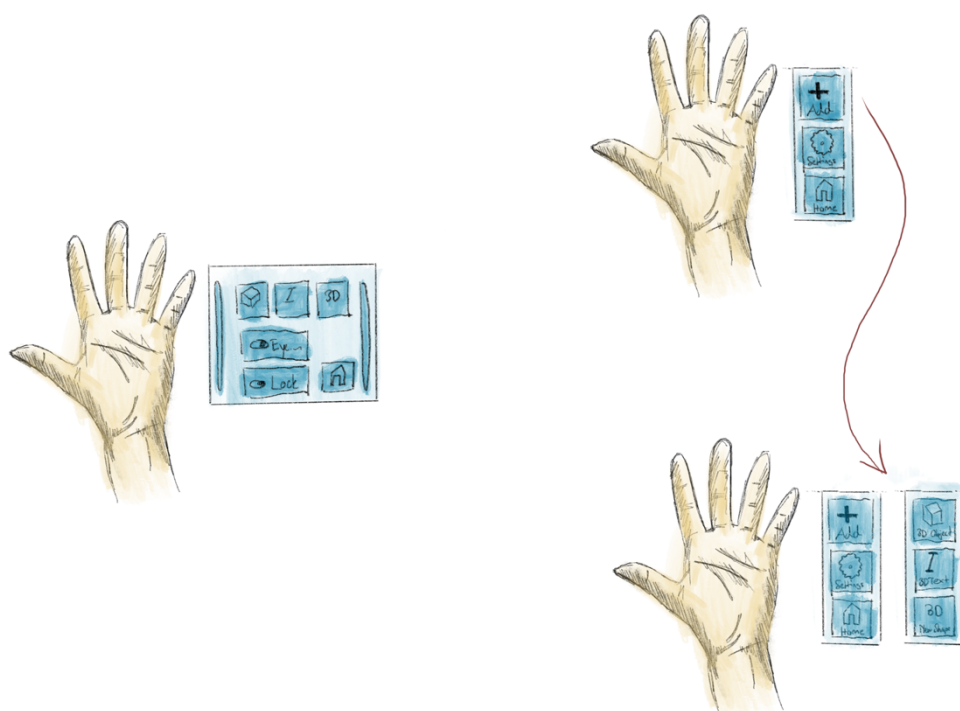
Figure 24: Sketch of two alternatives for an improved hand menu (i.e., main menu)

Hologram Menu

I decided to change the UI design of the process to place holograms. Instead of having an additional menu to select 3D objects floating around (like in the 3D Viewer), users will only choose what type of hologram they want to place (i.e., text, 3D object, or maybe draw lines in the future, etc.). After placing an object, a menu to change the object's appearance when selected shows up. This approach has the advantage that there is no other large menu floating around. In the usability test of iteration one, I found that the large menu can cause some issues as it can block the user from doing other things if they are not aware that they can close it or move it to the side.

Figure 25 shows two alternative designs for a hologram menu to change the appearance of a hologram. One option is to have a floating near menu at the bottom of the user's FOV (Figure 25 left). They can grab the menu, pin it to a specific position or have it follow them. Because this menu would be smaller than the prefabs menu from iteration 1, it would likely not block users from interacting with other elements. The second option would be to have a menu attached to the wireframes of the 3D object so that users can easily connect the menu and the object being edited.
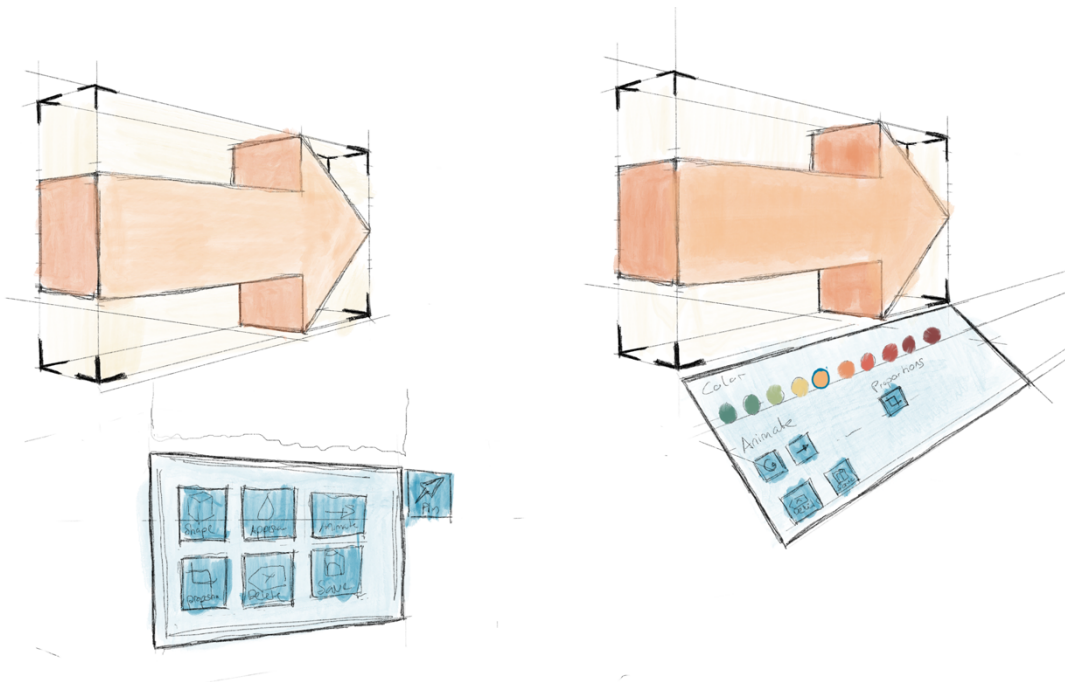
Figure 25: Sketch of two alternatives to a hologram menu where users can change the appearance of the hologram.

Furthermore, there are a couple of different solutions for how users can change the appearance of a hologram. For example, suppose they want to change the color of the hologram. In that case, there could be a design where people select a color from a predefined set of swatches like in figure 25 (right), or there is a mechanism to change the hue, saturation, and value of the hologram directly, either with some sort of slider mechanism (Figure 26) or by entering numerical values with a holographic keyboard.

Finally, I sketched two solutions for how submenus are presented in the hologram menu (Figure 26). The first solution would be to open a new slate whenever a user tries to access a submenu's contents (Figure 26, left), similar to the hand menu. The second solution is to display the submenu's contents on the same slide and hide any other content (Figure 26, right).

Other considerations for the design of the UI of this prototype included, among other things, signifying that the experiment was saved, displaying the eye gaze, and animating holograms. However, to not go beyond the scope of this thesis, I decided to limit this section to a discussion of possible designs of the menus and functionality described above.
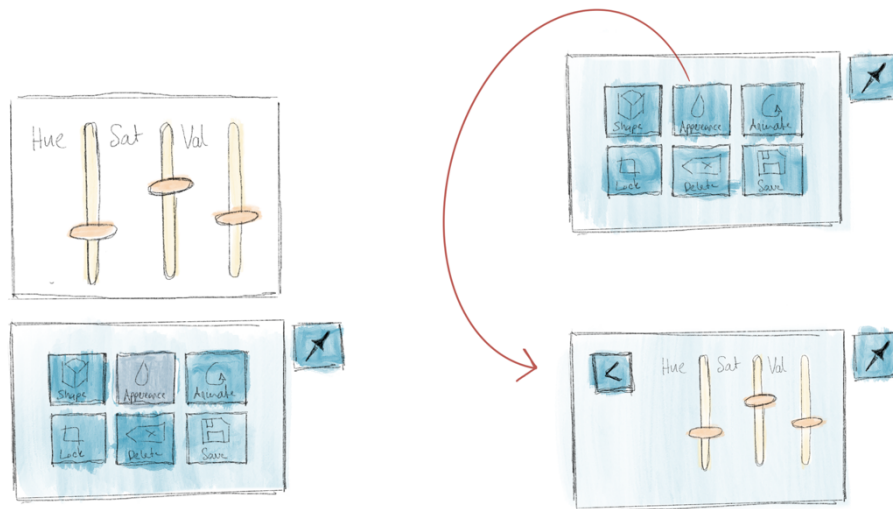
Figure 26: Sketch of different menu styles for the hologram menu

4.3.3 Prototype Development[25]

Based on the design from the last phase and the finding from the usability tests from the previous two phases, I built the third and final prototype for this thesis. At this stage, it was crucial to provide functionality and documentation for all the interaction levels, as discussed in iteration one. Technical considerations and software architecture were equally important during this iteration as the UI design. Both are essential parts of the UX design for the different personas, implementation details for the "techie" persona, and the UI for the "designer" and "scientist" personas. All the relevant technical details for the "techie" persona were documented in the code and in associated readme files.

Included Functionality

For the last prototype, I included all the user stories from iteration 1 (Appendix 8.4.1), all except the additional user stories from iteration 2 (Appendix 8.4.2), and finally, all the proposed user stories in iteration 3 (Appendix 8.4.3) except story III.XI (Displaying the eye gaze). While there is a button in the

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[25] To get access to the repository containing the source code, please get in touch with Tumasch Reichenbacher (tumasch.reichenbacher@geo.uzh.ch) of the GIVA group.

UI associated with story III.XI in the settings menu of the UI, the functionality was not implemented due to time constraints.

Description of the UI

Due to the extent and complexity of the final prototype, I decided to focus on the presentation of the aspects discussed in the idea generation section above. For example, because the home dialogue has only changed marginally from iteration two, I will not present it again here.

The central functionality of the last prototype is the ability to place and change the appearance of holograms. This process includes using the improved hand menu to place a hologram, then adjusting it according to the requirements of the experiment, and finally saving it as a cloud anchor.

The new hand menu

The hand menu was simplified for the last prototype, as discussed in the idea generation phase (Figure 24). Similar actions, such as adding different types of holograms or experiment settings, are now grouped in a submenu (Figure 27). This design makes the menu tidier and more effective. Furthermore, instead of the incomprehensible prefabs menu, users can now select "Add Asset" to add a choice of "3D Primitive", "3D Text", or a "glTF-file" (More on that in the technical summary). Selecting one of the three options from the submenu will then trigger the placement of a hologram directly in front of the user. They can then change its appearance according to visual variables known from cartography.
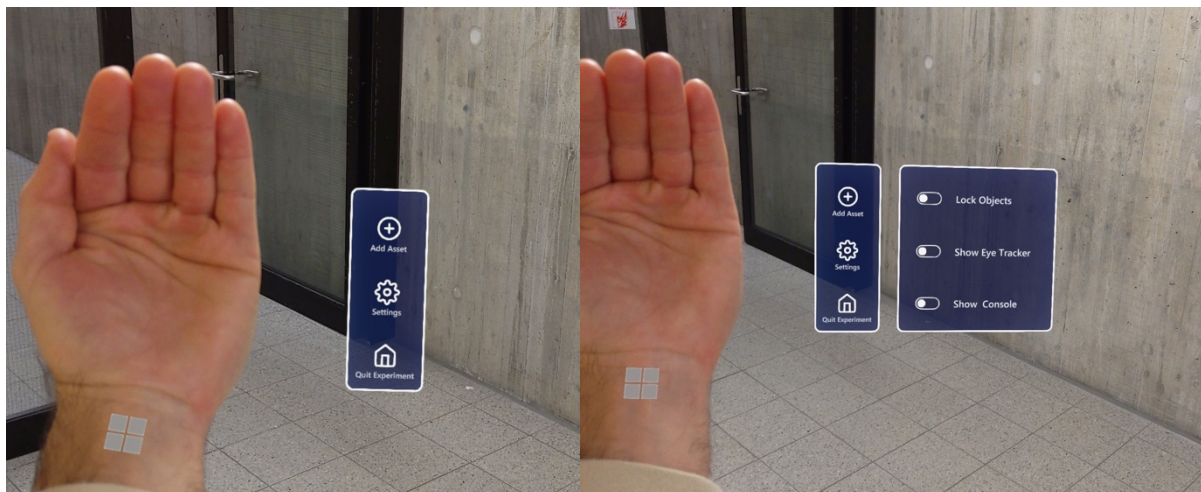
Figure 27: The improved hand menu (main menu) of the application.

The hologram menu

The hologram menu shows when the user places a 3D asset, as mentioned before (Figure 28) or when they select one by tapping it with their fingers. It is different for each type of asset (3D Primitive, 3D Text, or glTF-File). For consistency reasons, the layout of the hologram menu looks similar, and functionality like saving and deleting a hologram that exists for all holograms is placed in the same

spot. The menu is not attached to the hologram, so they can be moved independently. The hologram menu automatically places itself at the bottom of the user's FOV.

However, they can also decide to lock it in place and move it around as necessary by using the pin button in the top right corner and gabbing it on one of the edges. Since users can only edit one hologram at a time, and the hologram being edited is marked by the wireframes surrounding it (See Iteration 1), I am assuming that the connection between the menu and the hologram is clear. However, should the usability tests show that users have problems conceptually connecting the menu and hologram, having a design where the menu is connected to the hologram with something akin to a leash could solve the issue.
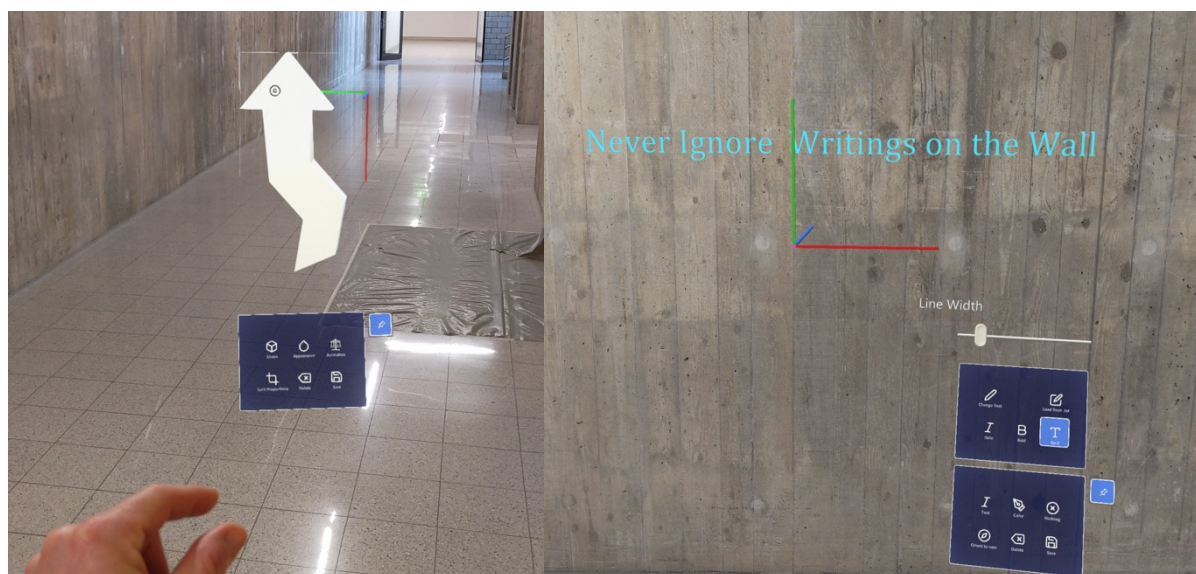
Figure 28: The hologram menu for 3D Primitives (left) and 3D text including the submenu to change the style of text (right)

3D Primitives

3D primitives are relatively simple 3D shapes with a monochromatic texture. They are ideal for most situations where researchers need arrows, pins, or other map symbols. Researchers can change the hologram's shape and color (hue, saturation, value, alpha). Moreover, they can animate the hologram so that it rotates or wiggles. Changing the location, size, orientation, and arrangement of holograms works the same as in the first prototype.

To edit a hologram and open the hologram menu, researchers can now either touch it with their fingers or air tap while pointing at it. To prevent experiment participants from accidentally opening the hologram menu, researchers can lock all the holograms in the settings (Figure 27, right).

Researchers now do not select a shape from the prefabs menu and place it; instead, they change it by opening the shape submenu in the hologram menu (Figure 29, top left). The shape selection submenu was inspired by the menu designed in iteration 1 (Figure 9). However, instead of grabbing the object like from a shelf, users just touch one of the boxes to change the shape of the currently selected hologram.

There are hue, saturation, value, and alpha sliders o change the color of a 3D primitive. Researchers can grab and move them much like they would use a physical slider. I have decided against an implementation with predefined color swatches because it gives the user more freedom to define a color. The usability test results will show whether having the sliders is usable. Alternatively, a solution where researchers enter values with the holographic keyboard could be tested. Moreover, users can select between three different textures; a regular one, an outlined one, and a glowing one.
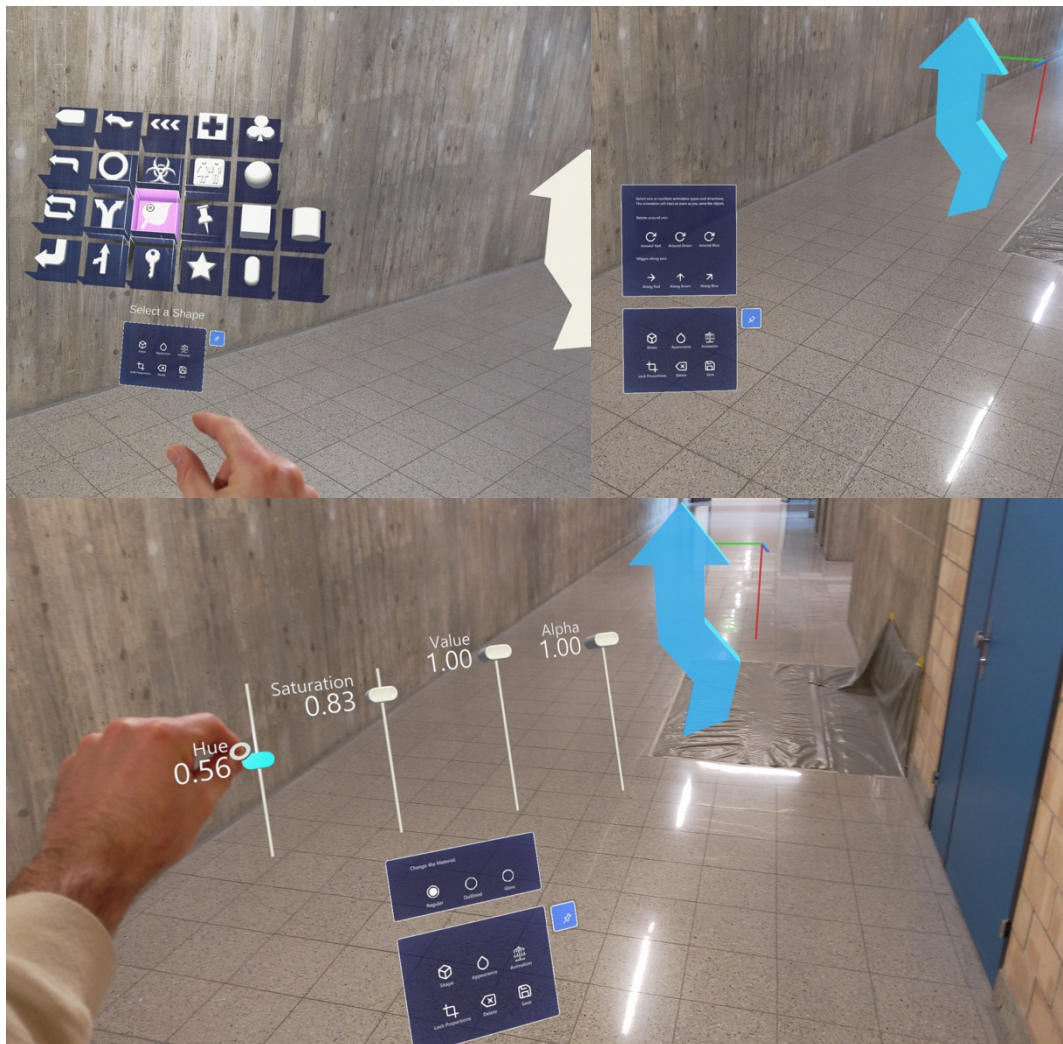
Figure 29: Submenus to change the shape (top left), and the color (bottom), and animate (top right) the hologram.

Finally, researchers can select simple predefined animations, so holograms can either wiggle along or rotate around one or multiple of the three principal axes shown whenever a hologram is selected (Figure 29, top right or Figure 30). Researchers can also choose whether they want to keep the proportions of a primitive or whether they want to distort it. Additional 3D primitives can be added to the Unity Editor's resources folder. Doing that, however, requires the project to be recompiled and deployed to the HoloLens.

3D Text

The functionality to add 3D text works similarly to adding a text field to a word document. After adding the asset, researchers can either type a text using the holographic keyboard or load text from a .txt-file. This functionality was added because I found in iteration two that using the holographic keyboard can be cumbersome for long texts.

Researchers can change the color of text like they can change the color of a 3D primitive. Moreover, they can make the text bold or italic and choose between a serif and non-serif font (Figure 28). However, text cannot be animated because that would probably make it hard to read. However, there is a toggle to decide whether the text should always face the user or keep the orientation defined by the researcher.

glTF Files

Finally, so that designers can add their own models, researchers can load glTF-models[26] from an URL (Figure 30). To do so, they can store the glTF in a public repository such as GitHub or a cloud storage platform such as dropbox. Then, they can add an URL referencing the file to a .txt-file. The file can then be opened from the application, and the glTF is loaded. While it is impossible to change the appearance of the glTF in the application, designers can use 3D software such as blender to create 3D objects precisely to their requirements. Still, glTFs can be moved, resized, rotated, and animated like a 3D primitive.
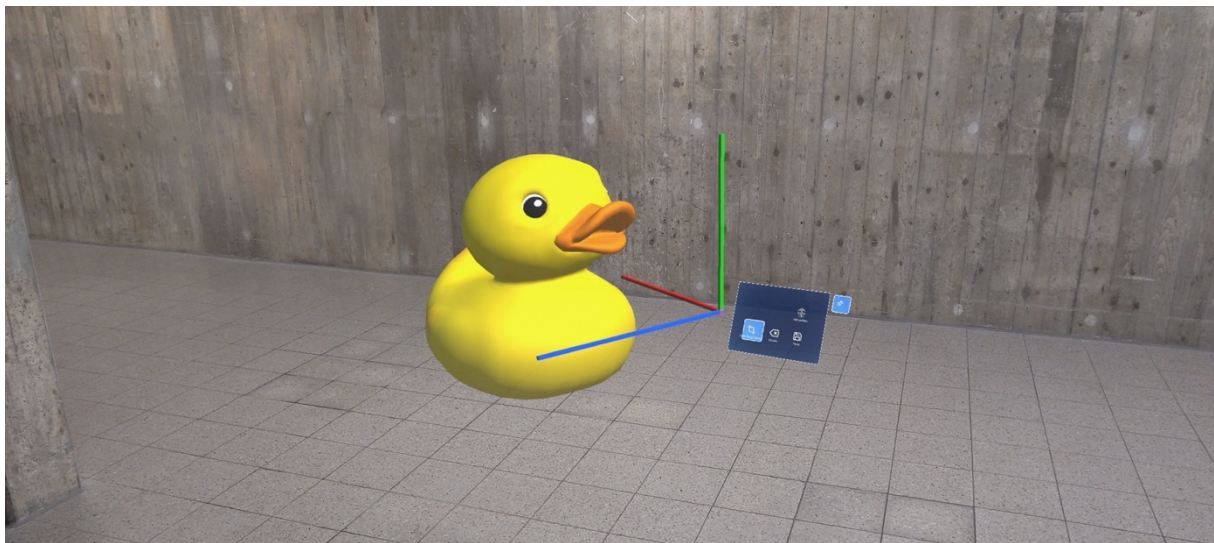
Figure 30: A rubber duck added to an experiment as a glTF-file.

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[26] *"glTF is a royalty-free specification for the efficient transmission and loading of 3D scenes and models by engines and applications."* (Khronos Group, 2022)

The save mechanism

The save mechanism was implemented in iteration 2. However, there was no signifier to tell the user that a hologram was saved. Therefore, whenever users add and save a hologram, a 3D status bar is displayed to show the progress and signify that the cloud anchor was saved (Figure 31).
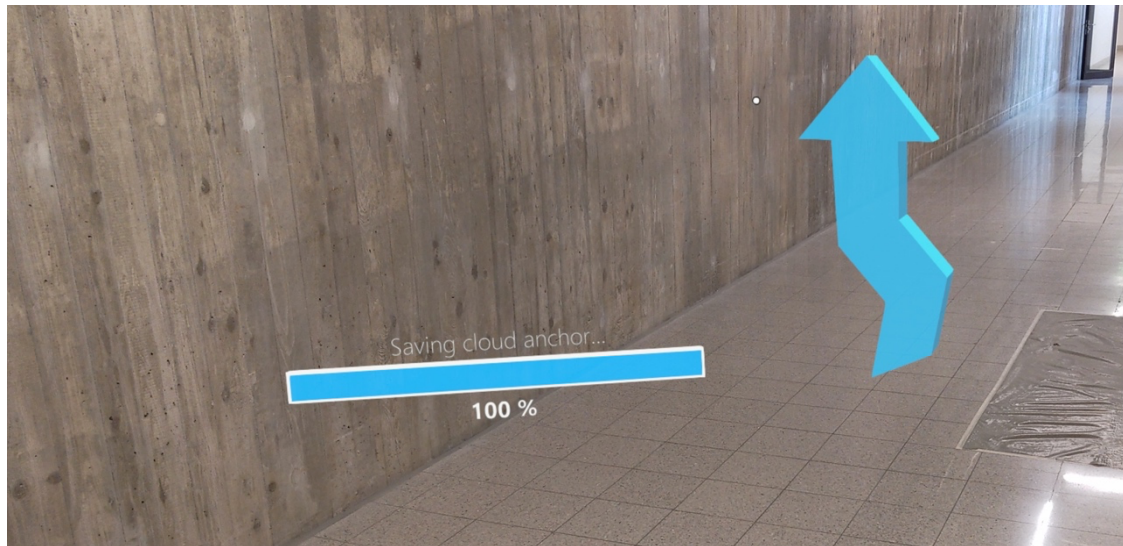
Figure 31: Status bar to show the process of a cloud anchor being saved and signify to the user that their work was saved.

Occlusion and Physics

The HoloLens' SLAM system maps the environment around the wearer in 3D. The mapped environment is represented as a 3D Object in Unity and can be used to occlude 3D objects naturally (Figure 32). While the result is not pixel-perfect on photos, it should be accurate enough to feel
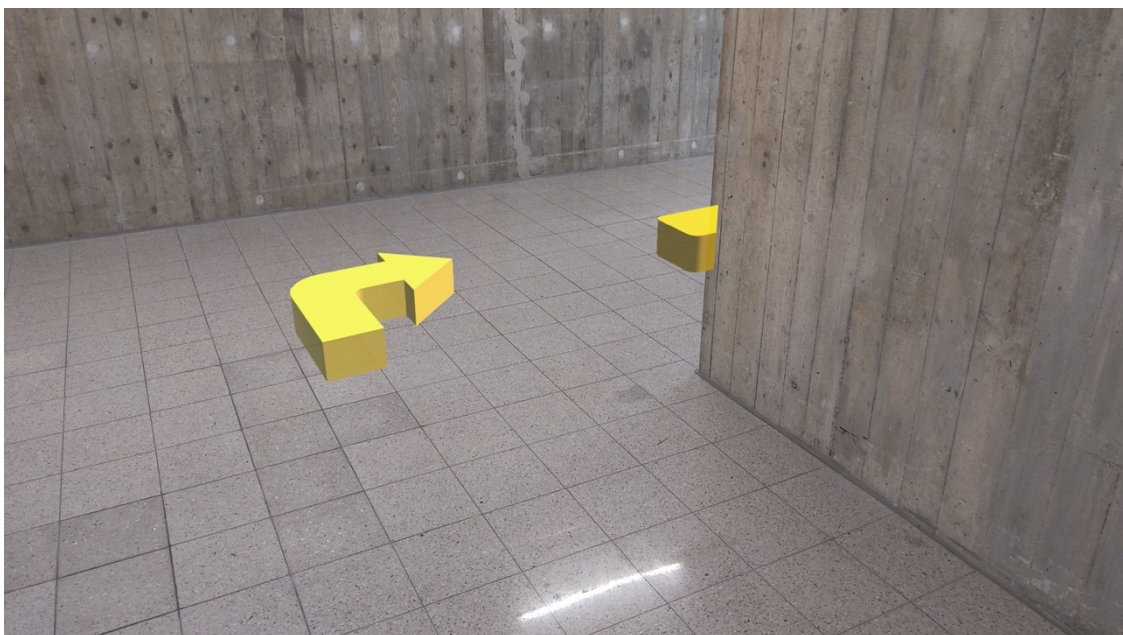
Figure 32: Occlusion of a 3D arrow by a physical wall.

natural. Similarly, the mapped environment could be used as a physical collider for 3D objects. Currently, 3D objects can be moved through walls. However, adding physical interactions such as gravity and collision with the environment could be done quickly in Unity should it be necessary.

Known Issues

There are several known issues with the final prototype. All of them are documented in the GitLab repository. However, for completeness, I decided to mention some of them here:

- The caret that displays the cursor's current position where the next character will be added when changing 3D text does not always show up in the right place, especially on multi-line text.
- The color of 3D text is sometimes not stored correctly.
- The size of primitives can sometimes not be recalled correctly.

4.3.4 Testing

To ensure that the final prototype is usable as intended and to be able to guide further development of the application, I qualitatively tested the prototype. To do so, I used the think-aloud method, like in the first iteration.

Questionnaire Results

Before the usability test, the participants filled in the same short questionnaire as in the first iteration. For this iteration, I had again 6 participants of which two were female and four were male. Again, none of the participants has performed a thinking-aloud before. While five performed the usability test in their native language (German), two performed it in their second language (English). Five of the participants have used both a VR headset and the HoloLens before, while one person has used neither.

Test Area and Tasks

The usability test was again performed between different aisles of lockers at the Irchel Campus of the University of Zurich. However, I chose another area that is a bit quieter this time (Figure 33). The participants were led to the starting point of the experiment and given information about the context. Their goal was to build a route with route instructions and digital landmarks. To make it more realistic, the participants were presented with a research question they were trying to answer and a hypothesis they wanted to prove. Still, the participants were given tasks one by one, as is standard practice in think-aloud (Section 3.5.1).

Before the start of the test, the participants were again informed how they could access the main menu (i.e., the hand menu) (Figure 27). Then the recording on the HoloLens was started, and the participants were given the first task and asked to raise their hands as soon as they were done. Appendix 8.3.2 shows the complete list of tasks. At the end of the test, I again tried to start a discussion about their experience to possibly learn more.

Figure 33:Images of the test area for the final think-aloud usability test at the Irchel Campus. Locker aisles that serve as a "labyrinth" and a corridor to follow over longer distances.

Test Outcome

The participants took, on average, 23 minutes to complete all the tasks, with a standard deviation of about 4.9 minutes, a minimum time of 19 minutes, and a maximum time of 31 minutes. The range of completion times was smaller this time, probably because most participants have used the HoloLens before. While people were unfamiliar with the application, they were familiar with many of the interaction paradigms indicating that they are indeed very well learnable.

Again, the hand menu worked very well as an entry point to the application. Thanks to the tidier layout, the participants could find relevant menu items faster. Moreover, the newly chosen nomenclature for actions is better than the one in the first iteration. The participants understood all the terms. While "Add Asset" was clear for all participants, "Add Hologram" could be an even better term. Finally, the submenus extend to the right when users access them, which causes some issues when users raise their right hand instead of their left hand to access a menu (Figure 34). While most of the time, participants still managed to access the item they wanted, they struggled sometimes and required multiple attempts, which can be annoying.

The participants had no trouble creating new holograms. However, if they were standing in front of a wall while creating the object, it could happen that it was instantiated behind the wall preventing them from seeing it. Even though they could just delete it and create it again, facing another direction to solve the problem, it was unclear to participants what had happened (Contradicts error recognition heuristic by Nielsen (1994a)). Moreover, the participants who were unfamiliar with the glTF file format needed help understanding how the functionality works. Yet loading a file after explaining the

process to them was easy for all participants. Therefore, this functionality, which I regard as an expert tool, should work fine with sufficient documentation.

Nonetheless, after the participants placed the hologram, changing its appearance with the hologram menu worked well. I expected that some users do not see the menu the first time it pops up or that it gets in the way sometimes. However, none of the participants had issues seeing the menu. Moreover, all the participants understood how to move the menu out of the way and pin it in place. Though, one participant had trouble finding the menu again after pinning it in a place a couple of meters away.

The use of the pinch sliders to alter the color of holograms required a period of acclimatization for

Figure 34: The submenus in the hand menu are sometimes blocked if users access it with their right hand.

most participants. Nevertheless, it worked sufficiently well once they became proficient in its usage. Because the saturation is at zero when a new hologram is initialized, some participants wondered why the hue was not changing. However, this could be solved by increasing the starting position of the saturation slider. Finally, all the participants also understood how to change the shape immediately. Although, one participant mentioned that it would be "cool" if they could just grab the hologram from the shelf and place it.

Animating the hologram also worked intuitively. The participants understood that the animation wiggles along or rotates around the red, green, and blue axes displayed when a hologram is selected (e.g., Figure 30). However, one participant mistook the axes as an interaction affordance and tried to grab them to rotate the hologram. To them, they signified interaction. To solve the problem, they could easily be hidden whenever users are not selecting an animation type for the hologram.

How to place 3D text was also clear to all the participants, although some needed time to find out how to change the text. After they found out, typing text with the holographic keyboard worked better than expected. Still, one participant said they are glad they don't have to write an essay with that keyboard. One participant who had trouble tapping the buttons also had difficulty with the keyboard.

These difficulties could have resulted from a poor calibration of the HoloLens or a lack of stereoscopic vision on the participant's part.

Most participants implicitly understood the save system and expected the experiment to be saved after uploading a spatial anchor. However, one participant expected the holograms to save automatically after every change and thought the save button was there to save the hologram so that it could be used again later. The same participant also tried to access the hand menu while still having the hologram menu open. It was also unclear why they couldn't access the menu, indicating that they had a different conceptual model of the save system. While not showing the hand menu prevented them from making a mistake, it was unclear what the problem was.

Finally, during three usability tests, the application crashed because of the video recording. While the application runs smoothly while recording most of the time, the application may crash when users perform GPU-intensive tasks. Such crashes would be less than ideal during an experiment that relies on a recording. This problem could probably be solved by having a laptop that runs all the computations and streams them to the HoloLens via a cable (i.e., holographic remoting).

Overall, all the participants managed to finish all the tasks with little help, indicating that the application is usable, with some minor issues that should be addressed in the future. Moreover, most participants got used to the lack of haptic feedback within a couple of tries. They, therefore, improved their interaction throughout the usability test, indicating that the interaction paradigm requires little time to get accustomed to.

5 Discussion

This thesis presents an application to study space-time decision-making and human behavior during indoor navigation with an MR HMD. Designing the UX and UI of the application according to the principles of HCD was a crucial element of the project. I will, therefore, first discuss the methodological approach to application development. Then, I will discuss the research questions presented in the introduction, as they were a central part of the HCD process. Furthermore, I will discuss the research goals in the context of the usability and utility of the application. Lastly, I will discuss the limitations of the application and how they relate to areas of further development.

5.1 Methodological Approach

The application in this thesis was developed according to the principles of HCD. This design paradigm is excellent for designing "everyday things" (D. A. Norman, 2002) like smartphones or mops (Weaver, 2018). However, there are criticisms that the inward-looking perspective of HCD creates a lot of collateral damage (Weaver, 2019). Moreover, HCD is arguably ill-suited to discuss the impact of MR interfaces on humans and the world in a broader context (Weaver, 2018). I will discuss the significance of research on the potential of MR interfaces to affect human behavior and, thus, the world around them later. In the context of this thesis, though, the choice of HCD to reach the goals mentioned in the introduction made sense. HCD has helped create an application that is useful and usable to researchers with varying degrees of technical skills.

5.1.1 Human-centered design

To discuss how HCD has influenced the development of the application, it is necessary to go back to the three principles of HCD by Rubin and Chisnell (2008) mentioned in section 3.3.1. These basic principles are reflected in the research questions that formed the initial basis of this project (Section 1.3). Moreover, they also determined most methods used at different project stages. First, the early focus on the target audience and their tasks is reflected in the literature review and the user personas created. Secondly, I performed think-aloud tests with a total of twelve participants and did a heuristic evaluation at different stages to test the application's usability. And finally, by using design thinking as outlined by Don Norman (2002), I iteratively improved the application. In the following sections, I will discuss the suitability of these methods for the project.

Early focus on the target audience and their tasks

To gain insight into the target audience and their tasks, I examined existing research on indoor navigation. This analysis helped to identify any research gaps and potential areas for further study

within the field, while also answering research question b). Doing this early in the development process helped to get an idea of how researchers have studied human navigation and designed relevant experiments. A systematic literature review with a quantitative analysis of research trends and topics could have yielded even more insights. However, the results from the review performed here still helped to identify and classify the target audiences' tasks and the kinds of experiments they want to perform while staying within the scope of this thesis.

The user personas presented in section 4.1.1 resulted from the research mentioned above and earlier experience. They helped to determine requirements, deduce user stories, and also helped to communicate design decisions. Moreover, they were a constant reminder that not all researchers have the same (technical) skills and research foci. However, user personas should usually be created based on contact with actual users as part of a collaborative process (Quesenbery, 2004). Otherwise, user personas can quickly develop into stereotypes resulting from preconceived opinions (Aquino & Filgueiras, 2005). Therefore, performing at least one contextual inquiry with a researcher actively studying MR indoor navigation might have arguably enabled the creation of more realistic user personas. Moreover, discussing them with peers could have improved them as well.

Despite the limitations of the user personas, they could effectively represent the target audience within the scope of this thesis. Moreover, they formed the basis for other artifacts created as part of the design process, such as the user stories created during each iteration or the three interaction levels the application must satisfy. In Conclusion, the user personas provided a meaningful answer to research question a) and were a solid foundation for the design process discussed here.

Empirical testing of application usage

The resulting prototype was tested for its usability at the end of each iteration. To do so, I used think-aloud and heuristic evaluation, two qualitative UX and UI design methods. Both methods are well-established for formative research and exploratory design (e.g., Nielsen, 1993b; Shneiderman et al., 2010).

Quantitative methods, such as collecting performance measures during usage, could have yielded an empirical basis for certain design decisions. However, they can be hard to collect, often require a lot of test subjects, and generally do not find individual usability problems (Nielsen, 1993b). Therefore, in the context of this thesis, the choice of usability testing methods below made sense.

Think-aloud

The think-aloud method was used in two iterations. Ideally, I would have used it in all three iterations. However, to save more time for the implementation of additional features, I decided to perform a heuristic evaluation of the save system presented in iteration two.

The think-aloud experiments performed at the end of iterations one and three successfully found usability issues and identified interactions that worked. Yet, thinking aloud can make users more efficient (Nielsen, 1993b), which is why the application should be evaluated during active use at some point in the future (Shneiderman et al., 2010).

Nonetheless, the strength of this approach was that it provided direct contact with potential users and brought to light many usability problems of the UI. However, because none of the participants was actively performing research with MR interfaces for indoor navigation, it did not provide any insight into the application's utility.

Heuristic Evaluation

To test the usability of the UI of the save system created in iteration two, I performed a heuristic evaluation. The evaluation did show some minor usability issues with the UI of the save system. However, according to the model by Nielsen and Landauer (1993)[27], one expert evaluator only finds about 30% of all usability problems. Considering that I am not an expert in heuristic evaluation at this stage, chances are that the actual percentage of usability problems encountered during that test is lower. Therefore, additional evaluators (According to Nielsen (1994b), about three to four) would have been needed. Moreover, because heuristic evaluation does not involve actual users, it cannot find any "surprises" related to their needs (Nielsen, 1993a).

In conclusion, performing the heuristic evaluation alone was probably not the ideal choice to test the application's usability. Finding three to four expert evaluators would have likely been challenging. Therefore, finding six more participants for another think-aloud after the second iteration would probably have made more sense.

Iterative Design

Throughout the project, I applied design thinking principles in three successive iterations. In the initial two iterations, I formulated and designed two distinct elements of the application (the basic interaction techniques and the save system). In the third iteration, these two elements were subsequently integrated into a final version of the application. As a result, the project management approach was likely a blend of an iterative and waterfall approach. Nonetheless, I continuously refined my answers to research question c), coming up with increasingly accurate and valuable user stories.

Don Norman (2002) argues that a central aspect of design thinking is to create and test multiple solutions to one problem in each iteration. Such an approach would facilitate a comparison of different solutions. Despite sketching numerous solutions during the idea generation phase, only one was implemented in Unity due to the scope of this thesis.

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[27] $ProblemsFound(\ i\ ) = N(1 - (1-l)^{\ i})$ where:
- i is the number of independent expert evaluators,
- $ProblemsFound(\ i\ )$ is the number of usability problems found by all evaluators
- N is the total number of usability problems
- l indicates the proportion of all usability problems found by one expert evaluator

An alternative approach would have been to create smaller prototypes during a larger number of iterations. In each of these prototypes, I could have then explicitly focused on implementing and testing individual UX and UI elements, such as changing the color of a hologram or placing and editing 3D text, among others. This approach would have likely provided more insights into optimal interaction techniques. However, it would have come at the cost of a sophisticated save system and an integrated final application.

5.1.2 Tools and Frameworks

Unity and the MRTK have helped to accelerate the development of prototypes for the HoloLens as compared to natively implementing them with C++. However, this approach also presented certain limitations. The functionality of Unity and the MRTK constrained the design of the UX and UI. For example, the hologram interaction techniques and the hand menu are predefined design elements from Microsoft's MR UX elements (Park, 2021). Using them could have hindered my ability to conceive novel, equally or more effective designs.

On the other hand, it is highly likely that Microsoft has designed and tested these UX elements through a similar process to the one employed in this project. Therefore, features like the hologram interaction techniques or the hand menu may already be the best from a large pool of ideas. Consequently, using the MRTK probably had more advantages than disadvantages, as it allowed me to focus on the essentials of the application presented here.

Using ASAs had similar implications on the application's design as using the MRTK. On the one hand, they offer a user-friendly and easy-to-use C# API for spatially anchoring and storing holograms. On the other hand, since they are proprietary, they are a black box with uncertain recall accuracy and precision. Despite this, there are no other viable alternatives to ASAs, because building a custom VIO system would have exceeded this thesis's scope and my software developer skills.

Furthermore, the usability tests conducted as part of this thesis have shown that the accuracy of hologram recall was sufficient for the intended purpose. However, applications geared at other use cases, such as medical procedures, require higher levels of accuracy and a better understanding of the accuracy and precision of the VIO system (Cutolo et al., 2014).

In conclusion, the use of frameworks and toolkits, such as the ones employed in this thesis, may have limitations in terms of flexibility, access to information (in the case of proprietary tools), as well as precision, and accuracy. However, using them also allows for faster development and a greater focus on the study's main objectives.

5.2 Final Application

This section will discuss the prototype created during the third iteration. The first and second prototypes were discussed in the results section because the next iteration relied directly on the findings and the implications of the previous iteration. Although this section is titled final application,

it is important to note that the application is by no means a final product. Instead, it is the final prototype created as part of this thesis.

While the resulting prototype in iteration three could potentially be used to conduct simple wayfinding experiments with holographic turn-by-turn instructions and landmarks, there are a lot of areas for improvement and extension. Thanks to the design and the platform it was built upon (Unity and the MRTK), it should be straightforward to add functionality and adapt it to changing academic or user requirements.

In the following paragraphs, the prototype created during the third iteration is discussed in the context of its usability and utility for the context at hand. Additionally, the technical aspects and their relation to the extensibility of the prototype will be examined. Finally, an analysis of the limitations of the current prototype and suggestions for addressing them in future iterations will be provided.

5.2.1 Usability

To provide an analysis of the application's usability, it is appropriate to refer to the five main usability characteristics by Jakob Nielsen (1992) as outlined in the methodology section. Firstly, the application will be discussed in the context of these five characteristics. Secondly, the specific usability issues encountered during the third usability test will be examined so that potential remedies can be proposed.

Nielsen's Usability Characteristics

Learnability

The think-aloud tests in the first and third iterations have shown that the fundamental controller-less hand interactions require little learning time, especially for users already familiar with the HoloLens. Moreover, most interactions like pressing buttons or moving, resizing, and rotating holograms generally require no instructions. Those interactions that do require directions, like accessing the hand menu, are easy enough to learn. At this stage, the application, therefore, has a high learnability. However, the more complex the application becomes in the future, the harder it might be to learn.

Efficiency

I have not measured the application's efficiency as part of the project. It would be interesting to get an understanding of how long it takes to set up an experiment and what changes would make it more efficient. Further improvements should, therefore, probably be made on the back of an actual small experiment performed with the application. Overall though, placing and editing holograms through direct manipulation within the environment is arguably a very efficient solution

Nonetheless, the efficiency of the application could certainly be improved through minor adjustments to the UI and the addition of new features. While using a computer to place 3D objects via a desktop interface might be more efficient, that approach is limited by the availability of accurate indoor digital maps and a higher mental load. For example, users would have to imagine the hologram while placing them before they can check whether it satisfies their requirements. Moreover, users who

prefer the functionality of a 3D rendering program (e.g., Blender) to create and edit their assets can import objects in the glTF format.

Memorability

Given that none of the participants of the think-aloud test of the first iteration participated in the third iteration, it is hard to make statements about the memorability of the application. However, as mentioned above, most of the features are readily learnable. Therefore, memorability at this stage plays a secondary role.

Error Frequency and Severity

The HoloLens hand interactions require some time to get accustomed to. Therefore, some of the participants of the think-aloud tests made many minor mistakes in the beginning. For example, they could not press the correct button or grab the corner of a hologram. However, these mistakes become less over time, and users can generally recover from them quite easily.

Moreover, some participants sometimes placed the wrong hologram (e.g., a cube instead of text). By deleting the hologram and placing a new one, users can recover. However, some participants expected an undo button as is, for example, recommended in the usability heuristics by Shneiderman et al. (2010).

Finally, there are general concerns with regard to error frequency and severity while wearing MR HMDs, especially in uncontrolled environments. Because the virtual content overlays the physical world, users could miss critical physical features such as stairs and get injured. These risks are slightly alleviated by the fact that the application runs on an OST HMD, where 3D features are always slightly translucent to the wearer, and in case of failure, users can still see their surroundings.

Nonetheless, Kim, Nussbaum and Gabbard (2016) have, for example, found that poorly designed interfaces for MR HMDs may distract workers and cause severe hazards in an industrial context. Therefore, the potential dangers of wearing MR HMDs in uncontrolled environments should be a core concern for all MR research and any experiment performed with the application presented here.

Subjective Satisfaction

During the think-aloud tests, the participants enjoyed using the application most of the time, prompting them to say things like "*Wow, this is cool*" or "[*Haha], that is so fun!*" (Translated from the German original). However, Derby and Chaparro (2021) highlight that it is crucial to be aware of the novelty effect when evaluating MR interfaces. The subjective satisfaction could possibly dimmish over time, and users can become annoyed by interactions they previously liked. In the case of the application presented here, only time will tell.

Usability Issues and their remedies

During the think-aloud test of the third iteration, I found several usability issues in the application. I will address those and propose potential remedies that could be implemented and tested in future development cycles.

First, I have identified several issues with the current hologram placement mechanism. Specifically, users may encounter problems because the hologram is instantiated in front of them, irrespective of their surroundings. Most notably, when the user stands directly in front of a wall or is too close to the newly instantiated hologram. Consequently, the hologram is not visible, which can cause confusion.

Given these problems, I believe it would be beneficial to consider redesigning the mechanism to an approach outlined in iteration 1 (Figure 9), where users grab holograms from a virtual shelf. Alternatively, it may be possible to develop a solution where users can air tap in a location where they want to place a hologram and then select the desired hologram from a pop-up menu (Figure 35). Both options would likely help to mitigate the current issues and improve the overall usability of the hologram placement mechanism.
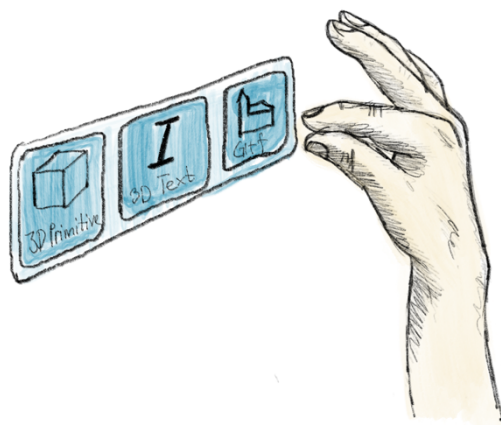
Figure 35: Sketch of an alternative mechanism to place holograms.

Second, some users had issued grabbing and moving the pinch sliders to change the color of a hologram (Figure 29, bottom). A simple solution would be to give them the option to either use the pinch slider or enter a value with the holographic keyboard. Then, everyone can decide what works best for them, which would comply with usability heuristic number three by Nielsen (1994a).

Third, several issues with the hologram menu led to errors. Some participants had difficulty remembering where they had pinned the hologram menu, leading to confusion and frustration. Therefore, to reduce the mental load on users, it would be beneficial to implement a function that allows them to recall the hologram menu to their FOV quickly.

Additionally, the fact that the hand menu is hidden while the hologram menu is open has caused some confusion. This feature is intended to prevent users from accidentally editing two holograms simultaneously or leaving the application without saving changes to a hologram. However, some believed that there was a bug in the application. As an alternative, it may be more effective to display the hand menu but gray out any functionality that is not currently available. Such a design would provide users with a clear indication of the available options while reducing confusion and potential errors.

Most of the usability issues mentioned above stem from users being able to edit holograms directly in the environment. In retrospect, focusing on the import of glTF files with minimal editing options for holograms and leaving the editing process to software specifically designed for it (e.g., Blender) could have allowed for developing other relevant features, such as automated data collection.

Finally, since I have not tested the save mechanism extensively, it is unclear whether it is conceptually entirely understandable. Despite not being evaluated during the think-aloud test of the third iteration, there are indications that participants had varying conceptual models of the system. As a result, it would be beneficial to reexamine the terminology – for example, do users create an experiment or a research environment – used in the save system and the UX design as part of any future development efforts.

Utility

At the time of publication, apart from the think-aloud tests, no actual experiment was performed with the application presented here. Therefore, it makes sense to consider the utility in the context of the previously discussed experiments outlined in section 2.5.1, as well as potential future wayfinding experiments that may be executed using it (Section 2.5.3).

The background focused on three aspects of these experiments; the style and design of route instructions, the hardware used to present these route instructions, and the evaluation criteria for these designs. While the hardware is primarily determined by the fact that the application was specifically designed for the HoloLens, the application does support a wide range of different types of turn-by-turn route instructions. Even though there are no built-in data collection methods, users can use external tools to gather various forms of data.

Reconstructing previous experiments

In section 2.5.1, I discussed various types of digital navigation experiments that have been conducted, including those performed with traditional WIMP interfaces on handheld devices (Table 1), those with handheld MR interfaces (Table 2), and those with MR HMDs (Table 3). To show the application's utility, I will discuss the merit and potential of reconstructing experiments performed on handheld devices with an MR HMD. Moreover, I will show how the application can be used to recreate experiments with MR HMDs which should give an indication of its utility for other experiments.

Mobile Devices

To understand how MR HMDs can improve upon state-of-the-art pedestrian navigation systems, it will be valuable to investigate the relative merits of turn-by-turn instruction delivered via an MR HMD compared to map-based approaches and turn-by-turn instructions on mobile devices in terms of navigation speed and success. Kray et al. (2003) compare several means of presenting route instructions on mobile devices. Correspondingly, "LandMarkAR" provides functionality to place different turn-by-turn route instructions in indoor environments and could be used for a similar comparison.

Additionally, several others, such as Beeharee and Steed (2006), Malaka and Benjamin (2008), as well as Rehrl et al. (2014), have evaluated navigation performance (speed and success) with map-based approaches in comparison to turn-by-turn instructions given on mobile devices. "LandMarkAR" could be used to extend these experiments to include a comparison with turn-by-turn instructions given by an MR HMD, further contributing to the understanding of the effectiveness of different navigation methods.

Others such as Ohm, Müller and Ludwig (2017) and Brügger, Richter and Fabrikant (2019) have used eye-tracking to evaluate user attention and the navigation system's effects on spatial learning during navigation. Moreover, Giannopoulos, Kiefer and Raubal (2015) used eye-tracking to present route instructions based on the user's current eye gaze. While "LandMarkAR" does not currently have functionality that uses the HoloLens' eye tracker, the MRTK does support eye tracking. Therefore, similar functionality could be easily integrated into the application.

Mixed Reality on Handheld devices

The studies in table 2 mainly focused on aspects such as user satisfaction and experience of MR and mobile devices. Only two papers reported on task completion speed and success. Only a few found advantages over traditional handheld interfaces regarding navigation speed and success, visual attention to the surroundings, and spatial knowledge acquisition. It would be possible to use "LandMarkAR" to compare handheld MR to MR HMDs in terms of the variables mentioned above and evaluate whether MR HMDs have advantages compared to other interfaces. While the current version of "LandMarkAR" could only be used to present route instructions via the HoloLens, thanks to the flexibility of Unity and the MRTK, the application could potentially be compiled for smartphones with only minor changes, therefore facilitating direct comparisons.

"LandMarkAR" could be used to reproduce most of the experiments mentioned in table 2. For example, as Mulloni, Seichter and Schmalstieg (2011) highlighted, MR functionality can significantly enhance the user experience of a pedestrian navigation system, improving decision-making and confirmation. They found that MR usage on a mobile device (i.e., looking raising the mobile phone) increases before and after an intersection. With "LandMarkAR", their design could be translated to an MR HMD to conduct similar experiments and further investigate their impressions. For example, an eye-tracker could be used to determine at which stages during navigation people need information from their MR HMD. Moreover, participants could be given an interactive map to observe in parallel with route instructions given through the HoloLens, to study when users rely on which information and its effects on their navigation performance and spatial learning.

Furthermore, studies such as those conducted by Dünser et al., (2012) or Zhang and Nakajima (2021) have explored the benefits of incorporating additional landmark information in a pedestrian navigation system and relying on those to guide users. With "LandMarkAR", researchers can conduct similar experiments by highlighting relevant indoor landmarks for users to follow. The user experience of turn-by-turn instructions given by a mobile MR system has also been studied by researchers like Kim et al. (2015) and Dong et al. (2021). "LandMarkAR" enables further examination of this topic by providing a platform for conducting similar experiments on an MR HMD.

Mixed Reality Head-mounted Displays

The field of indoor pedestrian navigation using MR HMDs is still relatively unexplored. "LandMarkAR" offers a valuable tool for researchers to conduct experiments in this area. Although it may not possess the advanced navigating functionality of systems such as the one presented by Bågling (2017) or the ability to display interactive map information as seen in the work of Wilson and Wright (2009), it could still be used to reproduce many of the studies outlined in table 3.

For instance, "LandMarkAR" possesses similar functionality to the 3D Viewer used by Morf (2022), allowing for similar studies on the effects of annotated landmarks on spatial learning. Additionally, it can be used to investigate the impact of MR HMDs on spatial learning, akin to the studies performed by Liu, Ding and Meng, (2021) and B. Liu et al. (2022).

Potential Novel Experiments

In section 2.5.2, I classified various novel experiments into four distinct categories: user-centered, interface-centered, task-centered, and design-centered studies. "LandMarkAR" provides the functionality to conduct experiments within any of these categories. However, its features make it particularly well-suited for design-centered studies. "LandMarkAR" allows for the placement of various types of route instructions and 3D elements emphasizing landmarks. For example, it could be used to study the effects of densely and sparsely placed route instructions on participants' cognitive load and spatial learning.

However, because MR HMDs are still relatively scarcely tested, it is crucial to establish baseline performance measures for MR HMD navigation systems through user-centered studies. These studies would not only compare navigation performance to state-of-the-art handheld systems but also examine the effects of MR interfaces on cognitive load and attention. For example, one participant in the think-aloud mentioned that they had to switch between the digital content and the physical world consciously; research could be conducted to understand how attention is shared between those two. Such research is crucial in identifying potential user hazards and could be conducted using "LandMarkAR" in conjunction with an eye-tracking system.

Once baseline performance measures have been established through user-centered studies, "LandMarkAR" can also be used for task-centered studies. For example, "LandMarkAR" can be used to explore how people navigate in stressful environments, such as emergency situations. Although, proper experiment design would be crucial for such an experiment. Nonetheless, such studies would provide valuable insights into how MR HMDs can aid in navigation under such conditions and how they compare to traditional navigation methods.

Similarly, task-centered studies could also investigate how MR HMDs can enhance navigation in specific tasks such as search and rescue operations, where time is of the essence and navigation accuracy is critical. As "LandMarkAR" does not fully support studies in outdoor environments, it does not directly support navigation experiments for search and rescue operations. However, it could also be used to study how MR HMDs can improve navigation in industries such as construction and manufacturing, where workers often need to navigate large, complex environments. Overall, task-

centered studies using "LandMarkAR" have the potential to provide valuable insights into the real-world applications of MR HMDs and how they can be utilized to enhance navigation in various scenarios.

In conclusion, as shown in the sections above, the versatility of "LandMarkAR" makes it possible to reproduce many experiments previously conducted with other interfaces on an MR HMD, enabling comparisons between them. Moreover, the functionality of "LandMarkAR" will allow researchers to study novel aspects of MR indoor navigation systems previously omitted. And finally, "LandMarkAR" can be easily extended to support many more use cases. Therefore, although it is no finished application, "LandMarkAR" does provide utility to researchers studying MR indoor navigation.

5.2.2 Limitations and areas for further development

As shown above, "LandMarkAR" is useful and usable for conducting multiple different MR navigation experiments. However, many areas of research are currently not supported. Yet, creating functionality to support these would have gone beyond this project's scope. Instead, the limitations present potential opportunities for further development and improvement of the application. Additionally, a couple of known issues[28] with the save system need fixing before adding new functionality.

One area for potential expansion of "LandMarkAR" would be to support the creation of augmented maps and exocentric navigational aids. While the current capabilities of "LandMarkAR" allow for the creation of augmented territories by placing various 3D objects, it does not have dedicated mapping and navigational functionality. Although implementing such features would require considerable effort, it could enable researchers to gather valuable further insights into holographic navigation. For example, it could aid in studying the safety implications associated with using augmented map navigation systems, as highlighted by Tran and Parker (2020).

It would therefore make a lot of sense to use the built-in eye tracker of the HoloLens. Not only to study user attention but also to build specific features based on the user's gaze. For example, researchers could create and test a feature where users are shown their relative position on a map whenever they focus on an important landmark. Such a strategy could possibly help users to build better mental representations of the space around them. Moreover, certain information and potentially distracting elements could be suppressed whenever the physical world requires the user's attention.

Adding the World Locking Tools to the application would present another possibility to collect data during an experiment. As mentioned above, the World Locking Tools provide a stable and consistent

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[28] As documented on GitLab

coordinate system created whenever the HoloLens maps a new environment. This coordinate system could then, for example, be used to export and analyze a participant's walked path during an experiment.

Moreover, as it is not known whether it is possible to wear an additional eye tracker below or above the HoloLens, it could make sense to include such functionality directly in the application. Eye gaze could be studied by having a small 3D ball that follows the wearer's line of sight. Researchers could then analyze recordings of each experiment for further insights. Another approach that would require the implementation of sophisticated data collection methods in the application would be to have functionality for measuring the amount of time each user looks at a hologram or the number of times their gaze enters and leaves the hologram. Both approaches could provide valuable insights into user attention and safety.

Furthermore, Morf (2022) has found that some participants have not seen holograms in some cases. While users can manually place pointers to holograms with "LandMarkAR", it would be possible to add functionality with the MRTK, where users would automatically get a message or an arrow continuously pointing at a relevant hologram or landmark as soon as they enter its vicinity.

Moreover, while the occlusion of 3D objects by physical objects such as walls or ceilings works well, there may be cases where it is not desirable. To address this, "LandMarkAR" could include functionality to turn off the occlusion for particular objects, enabling researchers to conduct navigation experiments with a beacon-based approach (e.g., J. Liu et al., 2022).

Finally, to accelerate the further development of "LandMarkAR", other contributors could evaluate whether it would be possible to integrate functionality either from "Landmarks" (Starrett et al., 2021) or "OpenMaze" (Alsbury-Nealy et al., 2022) into "LandMarkAR". Both were created with Unity and possibly contain functionality that could improve the application presented here.

In conclusion, there are several limitations and areas for expansion of "LandMarkAR". Nonetheless, it provides a solid foundation for "designers" and "scientists" to conduct studies with MR HMDs, and for "techies" to further develop and improve the application. With the inclusion of new features and improvement of existing ones, "LandMarkAR" can grow and become even more valuable.

6 Conclusion

MR technologies have the potential to become what Mark Weiser (1991) envisioned in his seminal piece "The Computer for the 21ˢᵗ Century": computing is gracefully embedded in the environment, and the boundaries between the digital and the physical world are blurred. MR interfaces potentially offer a more engaging and less distracting experience than screen-based interfaces, which could be especially beneficial for navigation tasks. However, this thesis has shown that there is a lot of research to be done before MR interfaces can be used for everyday activities such as navigating.

The effects of MR technologies on human cognitive aspects of technology usage, such as perception, emotion, presence, cognitive load, and attention, are currently unknown (Merino et al., 2020). Yet, modern computing has been shown to have a detrimental impact on many of the aspects above (e.g., Okoshi et al., 2015; Volkmer and Lermer, 2019). Mobile phones, for example, have been shown to be a primary reason for parents' disengagement with their children (Lemish et al., 2020). Now imagine how wearing smart glasses would affect their engagement levels and how that could impact their children. It is, therefore, crucial to study how and whether MR interfaces can alleviate these impacts or whether they are just supercharging current issues.

With "LandMarkAR", researchers can study the benefits and drawbacks of MR interfaces for human cognitive aspects during indoor navigation. In a first step, it makes sense to establish the efficacy of MR navigation systems with regard to essential performance variables such as navigation speed and success and compare them to other indoor pedestrian navigation systems. Moreover, researchers should study the benefits MR can have over physical signage. These results can then serve as a baseline for the utility of MR HMDs for indoor navigation. However, once the utility is established, researchers should focus on designing these systems so that they require less attention, are less distracting than mobile phones, allow users to focus on their surroundings and improve spatial learning. Ideally, MR interfaces should present a cocktail of useful spatial information so that users can infer new environments quickly and build the necessary cognitive representation, so they don't have to rely on the technology.

Still, it is unclear whether people will walk around with smart glasses in their everyday lives. Apart from the concerns of interface design, there are also substantial privacy concerns when people wear constantly running cameras everywhere they go. MR HMDs are, therefore, probably best used consciously for tasks or places such as museums or hospitals. In the future, the nurse who got lost in the hospital while moving me to the OR could wear smart glasses like the HoloLens. The interface will help them find the OR in time and present crucial patient information about my health status right in their field of view. The doctors will wear smart glasses during the operation, giving them all the information they need to perform the procedure successfully. However, there is still a long way to go, technically, but notably in the design of MR interfaces. Many challenges will have to be addressed and

concerns investigated. "LandMarkAR" is a first step in that direction and gives researchers a tool to study how MR can be used successfully for indoor navigation.

7 References

7.1 Literature

Alsbury-Nealy, K., Wang, H., Howarth, C., Gordienko, A., Schlichting, M. L., & Duncan, K. D. (2022). OpenMaze: An open-source toolbox for creating virtual navigation experiments. *Behavior Research Methods*, *54*, 1374–1387. https://doi.org/10.3758/s13428-021-01664-9/Published

Aquino, P. T., & Filgueiras, L. V. L. (2005). User modeling with personas. *ACM International Conference Proceeding Series*, *124*, 277–282. https://doi.org/10.1145/1111360.1111388

Aukstakalnis, S. (2016). *Practical augmented reality: A guide to the technologies, applications, and human factors for AR and VR*. Addison-Wesley Professional.

Azenkot, S., Ladner, R. E., & Wobbrock, J. O. (2011). Smartphone Haptic Feedback for Nonvisual Wayfinding. *ASSETS'11: Proceedings of the 13th International ACM SIGACCESS Conference on Computers and Accessibility*, 281–282.

Azuma, R., & Bishop, G. (1994). Improving static and dynamic registration in an optical see-through HMD. *Proceedings of the 21st Annual Conference on Computer Graphics and Interactive Techniques*, 197–204.

Azuma, R. T. (1997). A Survey of Augmented Reality. In *Presence: Teleoperators and Virtual Environments* (Vol. 6). http://www.cs.unc.edu/~azumaW:

Bågling, M. (2017). *Navigating to real life objects in indoor environments using an Augmented Reality headset* [Master's]. Umeå University, Faculty of Science and Technology.

Beeharee, A. K., & Steed, A. (2006). *A Natural Wayfinding-Exploiting Photos in Pedestrian Navigation Systems*.

Benko, H., Holz, C., Sinclair, M., & Ofek, E. (2016). NormalTouch and TextureTouch: High-fidelity 3D haptic shape rendering on handheld virtual reality controllers. *UIST 2016 - Proceedings of the 29th Annual Symposium on User Interface Software and Technology*, 717–728. https://doi.org/10.1145/2984511.2984526

Bertin, J. (1983). *Semiology of graphics*. University of Wisconsin press.

Brij, Y., & Belhadaoui, H. (2021). Virtual and Augmented Reality in school context: A literature review. *2021 3rd International Conference on Transportation and Smart Technologies, TST 2021*, 16–23. https://doi.org/10.1109/TST52996.2021.00010

Brown, T. (2008). Design Thinking. *Harvard Business Review*, *86*(6), 84–93.

Brügger, A., Richter, K. F., & Fabrikant, S. I. (2019). How does navigation system behavior influence human behavior? *Cognitive Research: Principles and Implications*, *4*(1). https://doi.org/10.1186/s41235-019-0156-5

Brunner-Friedrich, B., & Radoczky, V. (2005). Active landmarks in indoor environments. *International Conference on Advances in Visual Information Systems*, 203–215.

Buchanan, R. (1992). Wicked Problems in Design Thinking. *Design Issues*, *8*(2), 5–21.

Buchner, J., Buntins, K., & Kerres, M. (2022). The impact of augmented reality on cognitive load and performance: A systematic review. In *Journal of Computer Assisted Learning* (Vol. 38, Issue 1, pp. 285–303). John Wiley and Sons Inc. https://doi.org/10.1111/jcal.12617

Buley, L. (2013). *The user experience team of one: A research and design survival guide* (S. Anderson, Ed.). Rosenfeld Media.

Bury, G., Wen, Q., Tieto, V., Park, Y., Ferrone, H., & McCulloch, J. (2022). *Start designing and prototyping*. MRTK Design. https://learn.microsoft.com/en-us/windows/mixed-reality/design/design

Cipresso, P., Giglioli, I. A. C., Raya, M. A., & Riva, G. (2018). The past, present, and future of virtual and augmented reality research: A network and cluster analysis of the literature. *Frontiers in Psychology*, *9*(NOV). https://doi.org/10.3389/fpsyg.2018.02086

Çöltekin, A., Lochhead, I., Madden, M., Christophe, S., Devaux, A., Pettit, C., Lock, O., Shukla, S., Herman, L., Stachoň, Z., Kubíček, P., Snopková, D., Bernardes, S., & Hedley, N. (2020). Extended reality in spatial sciences: A review of research challenges and future directions. In *ISPRS International Journal of Geo-Information* (Vol. 9, Issue 7). MDPI AG. https://doi.org/10.3390/ijgi9070439

Cooper, A. (1999). *The inmates are running the asylum* [Book]. Vieweg+ Teubner Verlag.

Cooper, A. (2003). *About Face 2.0: The essentials of interaction design* (R. Reimann, Ed.; [2nd ed.]) [Book]. Wiley Publ.

Cross, N. (1982). Designerly ways of knowing. *Design Studies*, *3*(4), 221–227. https://doi.org/10.1016/0142-694X(82)90040-0

Cross, N. (2001). Designerly Ways of Knowing: Design Discipline versus Design Science. *Design Issues*, *17*(3), 49–55.

Cutolo, F., Parchi, P. D., & Ferrari, V. (2014). Video see through AR head-mounted display for medical procedures. *ISMAR 2014 - IEEE International Symposium on Mixed and Augmented Reality - Science and Technology 2014, Proceedings*, 393–396. https://doi.org/10.1109/ISMAR.2014.6948504

Dalton, R. C. (2003). The secret is to follow your nose: Route path selection and angularity. *Environment and Behavior*, *35*(1), 107–131. https://doi.org/10.1177/0013916502238867

de Cock, L., Ooms, K., van de Weghe, N., Vanhaeren, N., & de Maeyer, P. (2019). User Preferences on Route Instruction Types for Mobile Indoor Route Guidance. *ISPRS International Journal of Geo-Information*, *8*(11), 482. https://doi.org/10.3390/ijgi8110482

Derby, J. L., & Chaparro, B. S. (2021). The Challenges of Evaluating the Usability of Augmented Reality (AR). *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, *65*(1), 994–998. https://doi.org/10.1177/1071181321651315

DiBiase, D., MacEachren, A. M., Krygier, J. B., & Reeves, C. (1992). Animation and the role of map design in scientific visualization. *Cartography & Geographic Information Systems*, *19*(4), 201–214. https://doi.org/10.1559/152304092783721295

Doner, S., Zheng, J., McAvan, A. S., Starrett, M. J., Campbell, H., Sanders, D., & Ekstrom, A. (2022). Evidence for flexible navigation strategies during spatial learning involving path choices. *Spatial Cognition and Computation*. https://doi.org/10.1080/13875868.2022.2158090

Dong, W., Wu, Y., Qin, T., Bian, X., Zhao, Y., He, Y., Xu, Y., & Yu, C. (2021). What is the difference between augmented reality and 2D navigation electronic maps in pedestrian wayfinding? *Cartography and Geographic Information Science*, *48*(3), 225–240. https://doi.org/10.1080/15230406.2021.1871646

Downs, R. M. , & Stea, D. (Eds.). (1973). *Image and environment: Cognitive mapping and spatial behavior*. Transaction Publishers.

Dünser, A., Billinghurst, M., Wen, J., Lehtinen, V., & Nurminen, A. (2012). Exploring the use of handheld AR for outdoor navigation. *Computers and Graphics (Pergamon)*, *36*(8), 1084–1095. https://doi.org/10.1016/j.cag.2012.10.001

Edwards, E., Rolland, J. P., & Keller, K. P. (1993). Video see-through design for merging of real and virtual environments. *1993 IEEE Annual Virtual Reality International Symposium*, 223–233. https://doi.org/10.1109/vrais.1993.380774

Erickson, A., Reiners, D., Bruder, G., & Welch, G. F. (2021). Augmenting Human Perception: Mediation of Extrasensory Signals in Head-Worn Augmented Reality. *IEEE International Symposium on Mixed and Augmented Reality Adjunct, ISMAR-Adjunct*, 373–377. https://doi.org/10.1109/ISMAR-Adjunct54149.2021.00085

Feiner, S., Maclntyre, B., Höllerer, T., & Webster, A. (1997). A Touring Machine: Prototyping 3D Mobile Augmented Reality Systems for Exploring the Urban Environment. *Personal Technologies*, *1*, 208–217.

Field, A. (2014). *How to design and report experiments* (G. Hole, Ed.; Print on Demand) [Book]. Sage Publications.

Fitts, P. M. (1954). The Information Capacity of the Human Motor System in Controlling the Amplitude of Movement. *Journal of Experimental Psychology*, *47*(6).

Fonseca, F., Conticelli, E., Papageorgiou, G., Ribeiro, P., Jabbari, M., Tondelli, S., & Ramos, R. (2021). Use and perceptions of pedestrian navigation apps: Findings from Bologna and Porto. *ISPRS International Journal of Geo-Information*, *10*(7). https://doi.org/10.3390/ijgi10070446

Fraser, S., & Hedley, N. (2018). Augmented Reality and GIS. In *Comprehensive Geographic Information Systems* (Vol. 1, pp. 355–367).

Friis Damm, R., & Yu Siang, T. (2022). *The History of Design Thinking*. Interaction Design Foundation. https://www.interaction-design.org/literature/article/design-thinking-get-a-quick-overview-of-the-history

Fuest, S., Grüner, S., Vollrath, M., & Sester, M. (2021). Evaluating the effectiveness of different cartographic design variants for influencing route choice. *Cartography and Geographic Information Science*, *48*(2), 169–185. https://doi.org/10.1080/15230406.2020.1855251

Gamma, E., Johnson, R., Helm, R., Johnson, R. E., & Vlissides, J. (1995). *Design patterns: elements of reusable object-oriented software*. Pearson Deutschland GmbH.

Gardony, A. L., Brunyé, T. T., Mahoney, C. R., & Taylor, H. A. (2013). How Navigational Aids Impair Spatial Memory: Evidence for Divided Attention. *Spatial Cognition and Computation*, *13*(4), 319–350. https://doi.org/10.1080/13875868.2013.792821

Giannopoulos, I., Kiefer, P., & Raubal, M. (2015). GazeNav: Gaze-based pedestrian navigation. *MobileHCI 2015 - Proceedings of the 17th International Conference on Human-Computer Interaction with Mobile Devices and Services*, 337–346. https://doi.org/10.1145/2785830.2785873

GIVA. (2022). *The GIVA CAVE*. University of Zurich, Department of Geography. https://www.geo.uzh.ch/en/units/giva/services/cave-automatic-virtual-environment.html

Golledge, R. G. (1999). Human wayfinding and cognitive maps. In R. G. Golledge (Ed.), *Wayfinding Behavior: Cognitive Mapping and Other Spatial Processes* (pp. 5–45). Johns Hopkins University Press.

Golledge, R. G. (2003). Human Wayfinding and Cognitive Maps. In R. G. Golledge (Ed.), *The Colonization of Unfamiliar Landscapes* (1st Edition). Routledge.

Grinstein, G., Kobsa, A., Plaisant, C., Shneiderman, B., & Stasko, J. T. (2003). *Which comes first, usability or utility?* http://www.ics.uci.edu/~kobsa/papers/2001-INFOVIS-kobsa.pdf

Grudin, J. (1992). Utility and usability: research issues and development contexts. *Interacting with Computers*, *4*(2), 209–217.

Heskett, J. (2005). Utility and significance. In *Design: A Very Short Introduction*. Oxford University Press.

Hölscher, C., Meilinger, T., Vrachliotis, G., Brösamle, M., & Knauff, M. (2006). Up the down staircase: Wayfinding strategies in multi-level buildings. *Journal of Environmental Psychology*, *26*(4), 284–299. https://doi.org/10.1016/j.jenvp.2006.09.002

Huang, H., Gartner, G., Krisp, J. M., Raubal, M., & van de Weghe, N. (2018). Location based services: ongoing evolution and research agenda. *Journal of Location Based Services*, *12*(2), 63–93. https://doi.org/10.1080/17489725.2018.1508763

Hugues, O., Cieutat, J.-M., & Guitto, P. (2011). GIS and Augmented Reality : State of the Art and Issues. In *Handbook of Augmented Reality* (p. 855). Springer.

Hugues, O., Cieutat, J.-M., & Guitton, P. (2011). GIS and Augmented Reality: State of the Art and Issues. In F. Borko (Ed.), *Handbook of Augmented Reality* (p. 850). Springer.

ISO 9241: Ergonomics of Human-System Interaction, Pub. L. No. ISO 9241 (2013).

Ishikawa, T., Fujiwara, H., Imai, O., & Okabe, A. (2008). Wayfinding with a GPS-based mobile navigation system: A comparison with maps and direct experience. *Journal of Environmental Psychology*, *28*(1), 74–82. https://doi.org/10.1016/j.jenvp.2007.09.002

Jackson, M. A. (1995). *Software requirements and specifications a lexicon of practice, principles and prejudices* (M. A. Jackson, Ed.) [Book]. Addison-Wesley.

Kapaj, A., Lanini-Maggi, S., & Fabrikant, S. I. (2021). The Influence of Landmark Visualization Style on Expert Wayfinders' Visual Attention During a Real-World Navigation Task. *UC Santa Barbara GIScience Short Paper Proceedings*. https://doi.org/10.25436/E2NP44

Karimi, H. A. (2015). Preface. In H. A. Karimi (Ed.), *Indoor Wayfinding and Navigation*. Taylor & Francis Group.

Kelley, T., & Littman, J. (2001). *The art of innovation lessons in creativity from IDEO, America's leading design firm* (T. Kelley & J. Littman, Eds.) [Book]. Doubleday.

Kempe, J., Eichwede, B., & Ciborowius, T. (Eds.). (2019). *Moderne Architektur A-Z*. Taschen.

Khan, D., Cheng, Z., Uchiyama, H., Ali, S., Asshad, M., & Kiyokawa, K. (2022). Recent advances in vision-based indoor navigation: A systematic literature review. *Computers & Graphics*, *104*, 24–45. https://doi.org/10.1016/J.CAG.2022.03.005

Khronos Group. (2022). *glTF Runtime Asset Delivery*. https://www.khronos.org/gltf/

Kim, K. H., & Wohn, K. Y. (2011). Effects on productivity and safety of map and augmented reality navigation paradigms. *IEICE Transactions on Information and Systems*, *E94-D*(5), 1051–1061. https://doi.org/10.1587/transinf.E94.D.1051

Kim, M. J., Wang, X., Han, S., & Wang, Y. (2015). Implementing an augmented reality-enabled wayfinding system through studying user experience and requirements in complex environments. *Visualization in Engineering*, *3*(1). https://doi.org/10.1186/s40327-015-0026-2

Kim, S., Nussbaum, M. A., & Gabbard, J. L. (2016). Augmented Reality "Smart Glasses" in the Workplace: Industry Perspectives and Challenges for Worker Safety and Health. *IIE Transactions on Occupational Ergonomics and Human Factors*, *4*(4), 253–258. https://doi.org/10.1080/21577323.2016.1214635

Klippel, A., Hirtle, S., & Davies, C. (2010). You-are-here maps: Creating spatial awareness through map-like representations. *Spatial Cognition and Computation*, *10*(2–3), 83–93. https://doi.org/10.1080/13875861003770625

Kotonya, G., & Sommerville, I. (1998). *Requirements engineering processes and techniques* [Book]. Wiley.

Kray, C., Elting, C., Laakso, K., & Coors, V. (2003). Presenting Route Instructions on Mobile Devices. *IUI '03: Proceedings of the 8th International Conference on Intelligent User Interfaces*, 117–124.

Kunhoth, J., Karkar, A. G., Al-Maadeed, S., & Al-Ali, A. (2020). Indoor positioning and wayfinding systems: a survey. In *Human-centric Computing and Information Sciences* (Vol. 10, Issue 1). Springer. https://doi.org/10.1186/s13673-020-00222-0

Lawson, B. (1994). *How designers think: The design process demystified* (2nd ed.) [Book]. Butterworth Architecture.

Lawson, B. R. (1979). Cognitive Strategies in Architectural Design. *Ergonomics*, *22*(1), 59–68. https://doi.org/10.1080/00140137908924589

Leffingwell, D. (2011). *Agile software requirements: Lean requirements practices for teams, programs, and the enterprise* (1st edition) [Book]. Addison Wesley.

Lemish, D., Elias, N., & Floegel, D. (2020). "Look at me!" Parental use of mobile phones at the playground. *Mobile Media and Communication*, *8*(2), 170–187. https://doi.org/10.1177/2050157919846916

Lewis, C. (1982). *Using the 'Thinking-aloud' Method in Cognitive Interface Design*.

Lewis, M. G. (1987). The Origins of Cartography. In J. B. Harley & D. Woodward (Eds.), *The History of Cartography* (Vol. 1). The University of Chicago Press.

Lewrick, M. (2018). *The design thinking playbook mindful digital transformation of teams, products, services, businesses and ecosystems* (N. Langensand, P. Link, & L. Leifer, Eds.) [Book]. Wiley.

Liben, L. S., Kastens, K. A., & Stevenson, L. M. (2002). Real-world knowledge through real-world maps: A developmental guide for navigating the educational terrain. *Developmental Review*, *22*(2), 267–322. https://doi.org/10.1006/drev.2002.0545

Liu, B., Ding, L., & Meng, L. (2021). Spatial knowledge acquisition with virtual semantic landmarks in mixed reality-based indoor navigation. *Cartography and Geographic Information Science*, *48*(4), 305–319. https://doi.org/10.1080/15230406.2021.1908171

Liu, B., Ding, L., Wang, S., & Meng, L. (2022). Misleading effect and spatial learning in head-mounted mixed reality-based navigation. *Geo-Spatial Information Science*. https://doi.org/10.1080/10095020.2022.2137063

Liu, J., Singh, A. K., Wunderlich, A., Gramann, K., & Lin, C.-T. (2022). Redesigning navigational aids using virtual global landmarks to improve spatial knowledge retrieval. *Npj Science of Learning*, *7*(1), 17. https://doi.org/10.1038/s41539-022-00132-z

Lorenz, B., Ohlbach, H. J., & Stoffel, E.-P. (2006). A Hybrid Spatial Model for Representing Indoor Environments. In Carswell J & Tezuka T (Eds.), *Web and Wireless Geographical Information Systems* (Vol. 4295, pp. 102–112). Springer Lecture Notes in Computer Science. http://www.pms.ifi.lmu.de/

MacEachren, A. M. (1995). *How Maps Work*. Guilford Press.

MacEachren, A. M., Roth, R. E., O'Brien, J., Li, B., Swingley, D., & Gahegan, M. (2012). Visual Semiotics & Uncertainty Visualization: An Empirical Study. *IEEE Transactions on Visualization and Computer Graphics*, *18*(12), 2496–2505. https://doi.org/10.1109/TVCG.2012.279

MacIntyre, B., Gandy, M., Dow, S., & Bolder, J. D. (2004). DART: A Toolkit for Rapid Design Exploration of Augmented Reality Experiences. *UIST '04: Proceedings of the 17th Annual ACM Symposium on User Interface Software and Technology*, *6*(2), 197–206.

Malaka, R., & Benjamin, W.-F. (2008). Evaluation of an Augmented Photograph-Based Pedestrian Navigation System. *International Symposium on Smart Graphics*, 94–105.

Matthews, T., Judge, T. K., & Whittaker, S. (2012). How Do Designers and User ExperienceProfessionals Actually Perceive and Use Personas? *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, 1219–1228.

May, A. J., Ross, T., Bayer, S. H., & Tarkiainen, M. J. (2003). Pedestrian navigation aids: Information requirements and design implications. *Personal and Ubiquitous Computing*, *7*(6), 331–338. https://doi.org/10.1007/s00779-003-0248-5

Merholz, P. (2008). *Peter in Conversation with Don Norman About UX & Innovation*. Adaptive Path. https://podbay.fm/p/adaptive-path-podcast/e/1215053003

Merino, L., Schwarzl, M., Kraus, M., Sedlmair, M., Schmalstieg, D., & Weiskopf, D. (2020). Evaluating Mixed and Augmented Reality: A Systematic Literature Review (2009-2019). *Proceedings - 2020 IEEE International Symposium on Mixed and Augmented Reality, ISMAR 2020*, 438–451. https://doi.org/10.1109/ISMAR50242.2020.00069

Microsoft. (2022). *Entwicklung und Verwaltung von Applikationen und Lösungen für HoloLens 2*. https://www.microsoft.com/de-de/hololens/developers

Milgram, P., & Kishino, F. (1994). A Taxonomy of Mixed Reality Visual Displays. *IEICE Transactions on Information Systems*, *E77-D*(12). http://vered.rose.utoronto.ca/people/paul_dir/IEICE94/ieice.html

Miller, J., & Carlson, L. (2011). Selecting landmarks in novel environments. *Psychonomic Bulletin and Review*, *18*(1), 184–191. https://doi.org/10.3758/s13423-010-0038-9

Minecraft. (2022). *Home Hero Image*. https://www.minecraft.net/content/dam/minecraft/home/home-hero-1200x600.jpg

Montello, D. (2005). Navigation. In *The Cambridge Handbook of Visuospatial Thinking* (pp. 257–294). The Cambridge University Press. https://doi.org/https://doi.org/10.1017/CBO9780511610448.008

Montello, D. R., Hegarty, M., Richardson, A. E., & Waller, D. (2004). Spatial Memory of Real Environments, Virtual Environments, and Maps. In Allen G. L. (Ed.), *Human Spatial Memory: Remembering where* (pp. 251–285).

Montuwy, A., Dommes, A., & Cahour, B. (2019). Helping older pedestrians navigate in the city: comparisons of visual, auditory and haptic guidance instructions in a virtual environment. *Behaviour and Information Technology*, *38*(2), 150–171. https://doi.org/10.1080/0144929X.2018.1519035

Morf, N. (2022). *Improving the Acquisition of Spatial Knowledge when Navigating with an Augmented Reality Navigation System* [Master's]. University of Zurich.

Mower, N. (2022). *A Guide to Unity's Coordinate System (With Practical Examples)*. https://www.techarthub.com/a-guide-to-unitys-coordinate-system-with-practical-examples/

Mulloni, A., Seichter, H., & Schmalstieg, D. (2011). User experiences with augmented reality aided navigation on phones. *2011 10th IEEE International Symposium on Mixed and Augmented Reality, ISMAR 2011*, 229–230. https://doi.org/10.1109/ISMAR.2011.6092390

Nasar, J. L., & Troyer, D. (2013). Pedestrian injuries due to mobile phone use in public places. *Accident Analysis and Prevention*, *57*, 91–95. https://doi.org/10.1016/j.aap.2013.03.021

Netzwelt. (2022). *Tabletop AR*. https://img.netzwelt.de/dw2965_dh1668_sw2384_sh1341_sx2_sy163_sr16x9_nu1/picture/original/2019/07/ar-apps-256321.png

Newell, A., & Simon, H. A. (1972). *Human problem solving* [Book]. Prentice-Hall.

Nielsen, J. (1992). The Usability Engineering Life Cycle. *Computer*, *25*(3), 12–22. https://doi.org/10.1109/2.121503

Nielsen, J. (1993a). Usability Heuristics. In *Usability Engineering* (pp. 115–155). Academic Press.

Nielsen, J. (1993b). Usability Testing. In *Usability Engineering* (pp. 165–206). Academic Press.

Nielsen, J. (1993c). What is Usability? In *Usability Engineering* (pp. 23–43). Academic Press.

Nielsen, J. (1994a). *10 Usability Heuristics for User Interface Design*. NN Group. https://www.nngroup.com/articles/ten-usability-heuristics/

Nielsen, J. (1994b). *How to Conduct a Heuristic Evaluation*. NN Group. https://www.nngroup.com/articles/how-to-conduct-a-heuristic-evaluation/

Nielsen, J. (2012). *Thinking Aloud: The #1 Usability Tool*. Nielsen Norman Group. https://www.nngroup.com/articles/thinking-aloud-the-1-usability-tool/

Nielsen, J., & Landauer, T. K. (1993). A Mathematical Model of the Finding of Usability Problems. *INTERRCHI*, 206–213.

Nielsen, J., & Molich, R. (1990a). Heuristic evaluation of user interfaces. *CHI '90: Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, 249–256.

Nielsen, J., & Molich, R. (1990b). Improving a Human-Computer Dialogue. *Communications of the ACM, 33*(3), 338–348.

Norman, D. A. (1986). *User Centered System Design: New Perspectives on Human-computer Interaction* (1st ed.). CRC Press.

Norman, D. A. (2002). *The Design of Everyday Things* (6th ed.). MIT Press.

Norman, D., & Nielsen, J. (2012). *The Definition of User Experience (UX)*. Nielsen Norman Group. https://www.nngroup.com/articles/definition-user-experience/

Ohm, C., Bienk, S., Kattenbeck, M., Ludwig, B., & Müller, M. (2016). Towards interfaces of mobile pedestrian navigation systems adapted to the user's orientation skills. *Pervasive and Mobile Computing, 26*, 121–134. https://doi.org/10.1016/j.pmcj.2015.10.006

Ohm, C., Müller, M., & Ludwig, B. (2015). Displaying landmarks and the user's surroundings in indoor pedestrian navigation systems. *Journal of Ambient Intelligence and Smart Environments, 7*(5), 635–657.

Ohm, C., Müller, M., & Ludwig, B. (2017). Evaluating indoor pedestrian navigation interfaces using mobile eye tracking. *Spatial Cognition and Computation, 17*(1–2), 89–120. https://doi.org/10.1080/13875868.2016.1219913

Okoshi, T., Ramos, J., Nozaki, H., Nakazawa, J., Dey, A. K., & Tokuda, H. (2015). Attelia: Reducing user's cognitive load due to interruptive notifications on smart phones. *2015 IEEE International Conference on Pervasive Computing and Communications, PerCom 2015*, 96–104. https://doi.org/10.1109/PERCOM.2015.7146515

Oulasvirta, A., Tamminen, S., Roto, V., & Kuorelahti, J. (2005). Interaction in 4-Second Bursts: The Fragmented Nature of Attentional Resources in Mobile HCI. *CHI '05: Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*.

Pangilinan, E., Lukas, S., & Mohan, V. (Eds.). (2019). *Creating augmented and virtual realities: theory and practice for next-generation spatial computing*. O'Reilly.

Park, Y. (2021). *UX elements overview*. Microsoft Mixed Reality Documentation. https://learn.microsoft.com/en-us/windows/mixed-reality/design/app-patterns-landingpage

Parush, A., Ahuvia, S., & Erev, I. (2007). Degradation in spatial knowledge acquisition when using automatic navigation systems. *Lecture Notes in Computer Science (Including Subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics), 4736 LNCS*, 238–254. https://doi.org/10.1007/978-3-540-74788-8_15

Passini, R. (1981). Wayfinding: A conceptual framework. *Urban Ecology, 5*, 17–31.

Peddie, J. (2017). *Augmented Reality*. Springer International Publishing. https://doi.org/10.1007/978-3-319-54502-8

Péruch, P., & Wilson, P. N. (2004). Active versus passive learning and testing in a complex outside built environment. *Cognitive Processing*, *5*(4), 218–227. https://doi.org/10.1007/s10339-004-0027-x

Pontefract, D. (2018). *The Foolishness Of Fail Fast, Fail Often*. Forbes. https://www.forbes.com/sites/danpontefract/2018/09/15/the-foolishness-of-fail-fast-fail-often/?sh=4e397aad59d9

Puikkonen, A., Sarjanoja, A.-H., Haveri, M., Huhtala, J., & Häkkila, J. (2009). Towards Designing Better Maps for Indoor Navigation – Experiences from a Case Study. *MUM 2009: Proceedings of the 8th International Conference on Mobile and Ubiquitous Multimedia*.

Qiao, X., Ren, P., Dustdar, S., Liu, L., Ma, H., & Chen, J. (2019). Web AR: A Promising Future for Mobile Augmented Reality-State of the Art, Challenges, and Insights. *Proceedings of the IEEE*, *107*(4), 651–666. https://doi.org/10.1109/JPROC.2019.2895105

Quesenbery, W. (2004). Using Personas: Bringing Users Alive. *STC Usability SIG Newsletter-Usability Interface*.

Rankohi, S., & Waugh, L. (2013). Review and analysis of augmented reality literature for construction industry. *Visualization in Engineering*, *1*(9). https://doi.org/10.1186/2213-7459-1-9

Raubal, M., & Winter, S. (2002). Enriching Wayfinding Instructions with Local Landmarks. *International Conference on Geographic Information Science*, 243–259.

Rehman, U., & Cao, S. (2017). Augmented-Reality-Based Indoor Navigation: A Comparative Analysis of Handheld Devices Versus Google Glass. *IEEE Transactions on Human-Machine Systems*, *47*(1), 140–151. https://doi.org/10.1109/THMS.2016.2620106

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/10.1080/17489725.2014.946975

Roessel, J., Knoell, M., Hofmann, J., & Buettner, R. (2020). A Systematic Literature Review of Practical Virtual and Augmented Reality Solutions in Surgery. *Proceedings - 2020 IEEE 44th Annual Computers, Software, and Applications Conference, COMPSAC 2020*, 489–498. https://doi.org/10.1109/COMPSAC48688.2020.0-204

Rolland, J. P., Holloway, R. L., & Fuchs, H. (1995). A Comparison of Optical and Video See-Trough Head-Mounted Displays. *Telemanipulator and Telepresence Technologies*, *2351*, 376–307.

Rose, D. (2021). *Supersight: What Augmented Reality Means for Our Lives, Our Work, and the Way We Imagine the Future*. BenBella Books.

Roth, R. E. (2017). Visual Variables. In Richardson D., Castree N., Goodchild M.F., Kobayashki A., Liu W., & Marston R.A. (Eds.), *International Encyclopedia of Geography: People, the Earth, Environment and Technology* (pp. 1–11). John Wiley & Sons, Ltd. https://doi.org/10.1002/9781118786352.wbieg0761

Rubin, J., & Chisnell, D. (2008). *Handbook of Usability Testing: How to Plan, Design, and Conduct Effective Tests* (2nd ed.). Wiley Publishing Inc.

Ruddle, R. A., Volkova, E., & Bülthoff, H. H. (2013). Learning to walk in virtual reality. *ACM Transactions on Applied Perception*, *10*(2). https://doi.org/10.1145/2465780.2465785

Rudi, D., Giannopoulos, I., Kiefer, P., Peier, C., & Raubal, M. (2016). Interacting with maps on optical head-mounted displays. *SUI 2016 - Proceedings of the 2016 Symposium on Spatial User Interaction*, 3–12. https://doi.org/10.1145/2983310.2985747

Schmalstieg, D., & Höllerer, T. (2016). Introduction to Augmented Reality. In *Augmented Reality: Principles and Practice*.

Shneiderman, B., Plaisant, C., Cohen, M., Jacobs, S., Elmqvist, N., & Diakopoulos, N. (2010). *Designing the user interface: Strategies for effective human-computer interaction* (5th edition, inte...) [Book]. Addison Wesley.

Sorrows, M. E., & Hirtle, S. C. (1999). The Nature of Landmarks for Real and Electronic Spaces. *International Conference on Spatial Information Theory*, 27–50.

Stanley, P. (2022). *Open Peeps*. https://www.openpeeps.com

Stark, A., Riebeck, M., & Kawalek, J. (2007). How to Design an Advanced Pedestrian Navigation System: Field Trial Results. *IEEE International Workshop on Intelligent Data Acquisition and Advanced Computing Systems: Technology and Applications*, 690–694. http://www.ptv.de

Starrett, M. J., Mcavan, A. S., Huffman, D. J., Stokes, J. D., Kyle, C. T., Smuda, D. N., Kolarik, B. S., Laczko, J., & Ekstrom, A. D. (2021). Landmarks: A solution for spatial navigation and memory experiments in virtual reality. *Behavior Research Methods*, *53*, 1046–1059. https://doi.org/10.3758/s13428-020-01481-6/Published

Steele, P., Burleigh, C., Kroposki, M., Magabo, M., & Bailey, L. (2020). Ethical Considerations in Designing Virtual and Augmented Reality Products—Virtual and Augmented Reality Design With Students in Mind: Designers' Perceptions. *Journal of Educational Technology Systems*, *49*(2), 219–238. https://doi.org/10.1177/0047239520933858

Suh, A., & Prophet, J. (2018). The state of immersive technology research: A literature analysis. *Computers in Human Behavior*, *86*, 77–90. https://doi.org/10.1016/j.chb.2018.04.019

Sutherland, I. E. (1965). The Ultimate Display. *Proceedings of the IFIP Congress*, 506–508. http://www.cee.hw.ac.uk/courses/5ig2/1/ultimate_display.html

The British Design Council. (2020). *What is the framework for innovation? Design Council's evolved Double Diamond*. https://www.designcouncil.org.uk/news-opinion/what-framework-innovation-design-councils-evolved-double-diamond

Thompson, L. L., Rivara, F. P., Ayyagari, R. C., & Ebel, B. E. (2012). Impact of social and technological distraction on pedestrian crossing behaviour: an observational study. *Injury Prevention*, *19*(4), 232–237. https://doi.org/10.1136/injuryprev-2012

Tolman, E. C. (1948). Cognitive Maps in Rats and Men. *The Psychological Review*, *55*(4).

Tran, T. T. M., & Parker, C. (2020, April 25). Designing exocentric pedestrian navigation for AR head mounted displays. *Conference on Human Factors in Computing Systems - Proceedings*. https://doi.org/10.1145/3334480.3382868

Turner, A., Arya, H., Tieto, V., & Coulter, D. (2022). *Coordinate Systems*. Microsoft Mixed Reality Design Guidelines. https://learn.microsoft.com/en-us/windows/mixed-reality/design/coordinate-systems#spatial-anchor-persistence

Tversky, B. (1993). Cognitive Maps, Cognitive Collages, and Spatial Mental Models. In *Lecture Notes in Computer Science* (Vol. 716). Springer. http://www.cosit.info

Unity Manual. (2022). *Prefabs*. https://docs.unity3d.com/Manual/Prefabs.html

Vanclooster, A., van de Weghe, N., & de Maeyer, P. (2016). Integrating Indoor and Outdoor Spaces for Pedestrian Navigation Guidance: A Review. *Transactions in GIS*, *20*(4), 491–525. https://doi.org/10.1111/tgis.12178

Volkmer, S. A., & Lermer, E. (2019). Unhappy and addicted to your phone? – Higher mobile phone use is associated with lower well-being. *Computers in Human Behavior*, *93*, 210–218. https://doi.org/10.1016/j.chb.2018.12.015

Wake, B. (2003). *INVEST in Good Stories, and SMART Tasks*. XP123. https://xp123.com/articles/invest-in-good-stories-and-smart-tasks/

Weaver, J. (2018). Design Won't Save the World. *Medium*. https://medium.com/@hairyelefante/design-is-not-going-to-save-the-world-8985870471a5

Weaver, J. (2019). Human-Centered Design Is Broken. Here's a Better Alternative. *Medium*. https://medium.com/s/story/we-need-bee-centered-design-a1daf65e1679

Weiser, M. (1991). The Computer for the 21st Century. *The Scientific American*.

Whiteside, J., Bennett, J., & Holtzblatt, K. (1988). Usability Engineering: Our Experience and Evolution. *Handbook of Human-Computer Interaction*, 791–817. https://doi.org/10.1016/B978-0-444-70536-5.50041-5

Wilson, J., & Wright, P. (2009). Head-mounted display efficacy study to aid first responder indoor navigation. *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science*, *223*(3), 675–688. https://doi.org/10.1243/09544062JMES1213

Wunderlich, A., Grieger, S., & Gramann, K. (2022). Landmark information included in turn-by-turn instructions induce incidental acquisition of lasting route knowledge. *Spatial Cognition and Computation*. https://doi.org/10.1080/13875868.2021.2022681

Yussof, F. M. S., Sabariah, M. A., & Latiff, A. (2019). Augmented Reality: A Systematic Literature Review and Prospects for Future Research in Marketing and Advertising Communication. *Intelligent and Interactive Computing*, 459–473.

Zhang, Y., & Nakajima, T. (2021). Exploring 3D landmark-based map interface in ar navigation system for city exploration. *ACM International Conference Proceeding Series*, 220–222. https://doi.org/10.1145/3490632.3497858

8   Appendices

8.1 Consent form for think-aloud tests

Universität Zürich[UZH]

Consent Form

Usability Test for a Mixed Reality Research Application

Dear Participant,
Thank you for agreeing to take part in this usability test.

Contact Details of Responsible Experimenter
Patrick Luchsinger
M: 079 236 37 31
E-Mail: patrick.luchsinger@uzh.ch

Institution
This usability test will be conducted as part of the master's thesis by Patrick Luchsinger written at the GIVA Group at the Department of Geography of the University of Zurich.

Goals of the Usability Test
This usability test aims to collect direct information about how people interact with a HoloLens application intended to create usability experiments in mixed reality. The goal is to find exact problems with the interaction such that the application can be improved.

Voluntary Participation
Participation in this usability test is entirely voluntary. Participants may withdraw their consent to participate at any time without providing notice or reason. Should a participant wish to withdraw their consent, any data collected up until the point of withdrawal will be deleted.

Video recording
During the usability test, a video of your field of view and voice will be recorded by the HoloLens.

Data Confidentiality and Protection
During the usability test, non-sensitive, personally identifiable information will be recorded (i.e., age, gender). No sensitive personally identifiable information will be recorded. However, sensitive, personally identifiable information that could be inferred from video recordings will be protected as follows:

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- Any derivatives from video recordings will be anonymized.
- No sensitive personally identifiable information (e.g., name) will be published in any form.
- Video recordings will be kept on an encrypted, physical drive protected by a password only known to the experimenter listed above.

All the data collected during the usability test is stored for ten years due to a legal obligation. A local ethics committee may examine the data during this period.

Costs

During the time of this usability test, there will not incur any direct costs to the participant.

Benefits and Compensation for the Participants

This usability test offers no direct benefits for the participant. Moreover, the participant will not receive any financial compensation for participating in this usability test.

Termination of Participation

The participation will be canceled if participants:

- are not able to understand or adhere to the instructions of the experimenter.
- withdraw their participation at any point in time.

Consent

I have read and understood the above information and have received answers to any questions I asked. I consent to take part in the study.

Your Signature_____ Date_____

Your Name (printed)_____

Declaration of the experimenter: I certify that I have explained the nature of the usability test and how the data will be used. If there are any changes through the course of the user that affect the participant, I shall inform them immediately and seek approval. I certify that this study adheres to all legal obligations and complies with the national rules and international guidelines on human experimentation.

Signature of person obtaining consent_____Date_____

Printed name of person obtaining consent_____

8.2 Questionnaire for think-aloud tests

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Usability Test Questionnaire

Participant Nr. _____

Gender:

m   f   x

Native Language:

German   English   French   Other

Have you ever used a Virtual Reality or Mixed Reality Head-mounted Display?

y   n

Have you ever used the Microsoft HoloLens?

y   n

Have you ever participated in a think-aloud usability study?

y   n

Do not fill in. For experimenter only

Usability Test Language:

German   English   French

Usability Test Duration (mins)

_____

8.3 Think-aloud test tasks

8.3.1 Iteration 1

Task 1 (Warm-up)

- Use the menu at the starting location to calibrate the HoloLens for your eyes.
- Open the main menu of the HoloLens by pressing the Windows sign on your wrist.
- Do you have any questions at this stage about how the HoloLens works?
- Start the "Mixed Reality Research Tool". Do so by pressing on all Apps above the arrows to the right of the main menu and the selecting the mixed reality research tool.
- Start recording

Task 2

Basic Information:

By raising your hand with the palm facing towards you, you can access the main menu of the "Mixed Reality Research Tool".

Ultimate Goal:

Create a route from the starting location back to the cave lab

Step-by-Step:

From now on, follow these steps while continuously thinking out loud (i.e., verbalize your thoughts as you move through the user interface):

- Place a 3D Object of your choice at the starting location.
- Use 3D Objects of your choice to signify a route back to the CAVE lab.
- Place a 3D Object of your choice at the CAVE lab.
- Lock the 3D Objects in place such that they cannot be moved again.
- Indicate that you are done with Task 1 by raising your hand.

8.3.2 Iteration 3

Task 1 (Warm-up)

- Use the menu at the starting location to calibrate the HoloLens for your eyes.
- Open the main menu of the HoloLens by pressing the Windows sign on your wrist.
- Do you have any questions at this stage about how the HoloLens works?

- Start the "Mixed Reality Research Tool". Do so by pressing on all Apps above the arrows to the right of the main menu and the selecting the mixed reality research tool.
- Start recording

Task 2

Basic Information:

By raising your hand with the palm facing towards you, you can access the main menu of the "Mixed Reality Research Tool".

Context:

You are a researcher creating an experiment to study how mixed reality 3D landmarks affect the acquisition of spatial knowledge when finding a way in a new environment.

Your hypothesis is that 3D mixed reality landmarks improve the acquisition of spatial knowledge in environments that are sparse with physical landmarks.

To test your hypothesis, you want an experiment where you test your participants gathered spatial knowledge after following a route either with, or without digital landmarks.

For this usability test you will only build a route with digital landmarks.

Your 3D landmark of choice will be a virtual rubber duck. To give users information about the route you can use arrows, text, or any other object you deem meaningful.

I will give you step by step information.

Step-by-Step:

From now on, follow these steps while continuously thinking out loud (i.e., verbalize your thoughts as you move through the user interface):

- Place a Hologram of your choice at the starting location.
- Use 3D Objects of your choice to signify a route back to the CAVE lab.
- Use a duck, to place your first virtual landmark
- Make sure that it is animated to make sure, participants can actually see it.
- You're not quite happy with the placement of the rubber duck. Move again a little bit
- Continue to build the route
- Place a 3D Object of your choice at the CAVE lab.
- Now, comes the moment when you want to perform the experiment. To make sure that participants don't accidently move the landmarks, lock them in place.
- Indicate that you are done with Task 1 by raising your hand.

8.4 User Stories

8.4.1 Iteration 1

I.I.   Placing Holograms

Story:
As a researcher, I want to be able to place 3D holograms within an indoor environment such that I can create a mixed reality environment within which I can perform user studies related to human behavior and interaction with these environments.

Acceptance Criteria (Definition of Done):
- Researchers can use the HoloLens to place a 3D hologram in an indoor environment
- 3D holograms remain in the same position as long as the researcher needs them to

I.II.   Moving, rotating, resizing Holograms

Story:
As a researcher, I want to be able to move, rotate and resize 3D holograms I have previously placed in the environment such that I can place them according to the needs of the experiment I am planning.

Acceptance Criteria (Definition of Done):
- Researchers can move, rotate, and resize 3D holograms they have placed in the environment
- 3D holograms retain the same position, orientation, and size as long as the researcher changes the parameters again.

I.III.   Locking Holograms

Story:
As a researcher, I want to lock Holograms in place so that a subject cannot move them willingly or accidentally.

Acceptance Criteria (Definition of Done):
- A functionality lets researchers lock Holograms in place and unlock them to change their position, orientation, or size.

I.IV.   Save Experiment

Story:
As a researcher, I want to be able to save an experiment consisting of multiple holograms placed in space, such that I can revisit it later.

Acceptance Criteria (Definition of Done):
- Researchers can save the configuration of an experiment to change it later.
- Researcher can save the configuration of an experiment to conduct it multiple times.

I.V.   Load Experiment

Story

As a researcher I want to be able to load an experiment I have previously created such that I can change it or such that I can conduct it multiple times without having to set it up again every time.

Acceptance Criteria (Definition of Done):
- Researchers can load the configuration of an experiment to make changes to it.
- Researcher can load the configuration of an experiment to conduct it.

I.VI.   Undo/Redo Command

Story

As a researcher I want to be able to undo or redo a command (i.e., an action, e.g., to create a hologram, or to move a hologram) such that I can correct an unwanted command.

Acceptance Criteria (Definition of Done):
- Researchers can undo an unwanted command.
- Researchers can redo an unwanted undo command.

8.4.2 Iteration 2

II.I.   Create New Experiment

Story:

As a researcher, I want to be able to create a new experiment containing no holograms, such that I can place holograms needed to study a particular aspect of MR navigation.

Acceptance Criteria (Definition of Done):
- There is functionality to create a new experiment.
- As soon as a user has created an experiment, it is loaded.

II.II.   Name Experiment

Story:

As a researcher, I want to be able to give a new experiment a name so I can find it again later.

Acceptance Criteria (Definition of Done):
- There is functionality to type the name of the experiment.

II.III.   Save Experiment

Story:

As a researcher, I want to be able to save an experiment consisting of multiple holograms placed in space, such that I can revisit it later.

Acceptance Criteria (Definition of Done):
- Researchers can save the configuration of an experiment to change it later.
- Researchers can save the configuration of an experiment to conduct it multiple times.

II.IV.   Load Experiment

Story

As a researcher, I want to be able to load an experiment I have previously created such that I can change it or such that I can conduct it multiple times without having to set it up again every time.

Acceptance Criteria (Definition of Done):
- Researchers can load the configuration of an experiment to make changes to it.
- Researchers can load the configuration of an experiment to conduct it.
- Once an existing experiment is loaded, all the previously created holograms are visible again in the same configuration as the last time the experiment was opened.

II.V.   Quit Experiment

Story

As a researcher, I want to be able to quit an experiment so that I can either create a new experiment or open an existing one.

Acceptance Criteria (Definition of Done):
- There is functionality that allows researchers to leave an experiment
- Once a user leaves an experiment, the holograms of that experiment are no longer visible.

II.VI.   Object permanence

Story

As a researcher, I want to be able to see a hologram in the same place as I placed it when I revisit a place and open the same experiment.

Acceptance Criteria (Definition of Done):
- Holograms stay in the same position even when users leave their vicinity.
- Holograms do not disappear unless the user expects them to.

Additional User Stories

In addition to the essential user stories above, there are user stories that correspond more with interaction level B). These do not have a high priority at this stage but could be valuable in the future. They would also probably require a more complex save system.

II.VII.   Reuse existing holograms

Story

As a researcher, I want to be able to reuse and combine existing holograms in a new experiment so that I don't have to place them again.

Acceptance Criteria (Definition of Done):
- There is functionality that allows researchers to identify existing holograms and combine them into a new experiment.

II.VIII.   Query the location of holograms

Story

As a researcher, I want to be able to query the location of holograms with respect to other holograms so that I can geocode the holograms of an experiment relatively easily.

Acceptance Criteria (Definition of Done):
- There is functionality that allows researchers to query for a hologram's x, y, and z coordinates.
- There is functionality that returns coordinates and other attributes of all the holograms in an experiment

II.IX.   Query participant path

Story

As a researcher, I want to be able to query for the path a participant has followed during an experiment so I can run additional analyses.

Acceptance Criteria (Definition of Done):
- There is functionality that allows researchers to query for a chain of coordinates relative to holograms with timestamps.
- These coordinates represent the path followed by an experiment participant.

8.4.3 Iteration 3

III.I.   3D Hologram shape

Story:

As a researcher, I want to be able to change the shape of a hologram I have placed such that I can study the effects of different types of route instructions.

Acceptance Criteria (Definition of Done):
- There is functionality to select one of many predefined shapes.

III.II.   Upload shape

Story:

As a "Designer", I want to be able to use any shape or 3D object I have created using 3D software, such as blender, as a hologram such that I can use them in my studies.

Acceptance Criteria (Definition of Done):
- There is functionality that lets users add external 3D objects as holograms to an experiment.

III.III.   Add shape in Unity

Story:

As a "Scientist" or "Techie", I want to be able to easily add 3D shapes to Unity so that they can be used as holograms in a new version of the application.

Acceptance Criteria (Definition of Done):
- There are clear instructions for how to add 3D shapes to the software in Unity.

III.IV.   Lock/Unlock Proportions

Story:

As a researcher, I want to be able to lock or unlock the proportions of a hologram when resizing so that I can change the appearance and build complex shapes from simple primitives.

Acceptance Criteria (Definition of Done):
- There is functionality to lock and unlock the proportions of a hologram when resizing.

III.V.   Change Color
Story:
As a researcher, I want to be able to change the color of a 3D hologram so that I can study the significance of the cartographic visual variables hue, saturation, and value for MR navigation.

Acceptance Criteria (Definition of Done):
- There is functionality to change the color of a 3D hologram.

III.VI.   Change Opacity
Story:
As a researcher, I want to be able to change the opacity of a 3D hologram so that I can study the significance of the cartographic visual variable transparency for MR navigation.

Acceptance Criteria (Definition of Done):
- There is functionality to change the opacity of a 3D hologram.

III.VII. Animate hologram
Story:
As a researcher, I want to be able to animate a 3D hologram so that I can study the significance of the visual variable motion for MR navigation.

Acceptance Criteria (Definition of Done):
- There is functionality that lets users define an axis along or around which an object can move or rotate.
- There is functionality that lets users define an interval with which a hologram should blink.

III.VIII. 3D Text as hologram
Story:
As a researcher, I want to be able to add 3D text as a hologram to an experiment so that I can study the suitability of textual route instructions or embedded environmental information for MR Navigation.

Acceptance Criteria (Definition of Done):
- Users can add and edit 3D text like they can other 3D holograms.
- Users can type text on a holographic keyboard.
- Users can add text from a .txt file.

III.IX.   Orient text to user
Story:
As a researcher, I want to be able to have 3D text that is always oriented toward the user.

Acceptance Criteria (Definition of Done):
- There is functionality that lets users automatically orient 3D text toward the user.

III.X.   Understanding the save mechanism

Story:

As a researcher, I want to be able to know when a hologram and experiment is saved so that I am sure that I can close the application and recover my work later.

Acceptance Criteria (Definition of Done):

- There is a signifier that lets users know when a hologram and an experiment is saved.

III.XI.   Display Eye Gaze

Story:

As a researcher, I want to be able to display the eye gaze of the wearer of the HoloLens such that I can analyze visual attention in a POV recording of the experiment.

Acceptance Criteria (Definition of Done):

- There is some 3D object (e.g., a Ball) that follows the eye-gaze
- The 3D object can be shown or hidden.

8.5 Heuristic Evaluation

8.5.1 Iteration 2

Visibility of system status

- Is given in all three dialogues.
- In the home screen through the welcome message.
- In the create screen through the prompt to type a name.
- In the select existing experiment through the prompt to select an existing experiment.

Match between system and real world

- Clicking a button has been shown to work in the last usability test. The physical pressing motion require to click it, matches the real world perfectly (Though no haptic feedback).
- The term experiment should be familiar to researchers, though it must be evaluated whether they intuitively understand what it means.

User control and freedom

- The UI flow is clear. The user controls where they want to go. Should the accidentally select the wrong option, they can always go back.

Consistency and standards

- The term experiment is consistently applied.
- The flow of the UI is really simple and elements such as buttons and lists are familiar to users from other systems.

Error prevention

- The UI does not offer any opportunities for errors except typing an experiment name that is already in use.
- However, because the slates always follow the user's gaze, they could potentially miss an important physical feature and for example fall down a stair while trying to press a button. However, because the dialogues are relatively small and semi-translucent, this danger should be reduced. Maybe a warning message could help, though that could again lead people to trip.

Recognition rather than recall

- The user does not have to remember any information apart from how they have called their experiment. However, they can always recall through opening an experiment and seeing whether this is what they look for.

Flexibility and efficiency of use

- At that stage there are no shortcuts. However, there are options to add voice recognition to type the name of the experiment so that users don't have to use the holographic keyboard too often.

Aesthetic and minimalist design

- Aesthetic is subjective, but it is very minimalist.

Help users recognize, diagnose, and recover from errors

- If users type a name that is already in use, they are informed
- If users accidentally open the wrong experiment they can only realize if they see a hologram that they would not expect at a certain position, or if there is one missing.

Help and documentation

- The save system is thoroughly documented in code. However, there is no user guide available apart from the thesis.

8.6 Personal Declaration

I hereby declare that the submitted thesis is the result of my own, independent work. All external sources are explicitly acknowledged in the thesis.

Patrick Luchsinger, 31st January 2023