University of Zurich[UZH]

The Role of Virtual Landmarks in Mixed-Reality Indoor Navigation: Impact on Spatial Learning, Situation Awareness, and User Workload

GEO 511 Master's Thesis

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Abstract

The Global Navigation Satellite System (GNSS) is frequently used for outdoor wayfinding. However, GNSS is ineffective for indoor navigation because GPS signals fail to pass through walls, resulting in imprecise indoor localization. Mixed Reality (MR) technology offers a potential solution to that issue and could serve as an automatic indoor navigation system using holographic navigation aids. Previous studies showed that while automatic navigation systems enhance navigation performance, they can also decrease spatial knowledge acquisition by reducing human effort and dividing the attention between the environment and navigational aids. Additionally, augmented elements can decrease situation awareness and influence spatial learning because people pay more attention to holograms than their physical surroundings.

The main goal of the study was to evaluate a new design by integrating virtual landmarks as symbolic recreations in front of the physical landmarks to increase situation awareness and enhance spatial learning acquisition during indoor navigation in MR using the Microsoft HoloLens 2. A between-subject experiment (virtual landmark group vs control group) was conducted, where the participants were guided through a building with holographic navigation arrows using this specific design. Following the navigation task, participants were tested on their acquired spatial knowledge, including landmark knowledge and route knowledge. The secondary goal was to explore how this design affects the workload during navigation and whether the emotional stress when solving the post-navigational questionnaires is reduced because people feel more confident in their knowledge after the navigation with the specific design, measured with the NASA Task Load Index (NASA-TLX) and the Empatica E4 wristband.

The group exposed to virtual landmarks during navigation shows a significant increase in spatial learning compared to the control group. However, this effect is limited to landmark knowledge acquisition, and no significant difference in route knowledge acquisition is found between the groups. The results show a significant difference between the landmark types, indicating that 3D objects are memorized better than wall objects. Additionally, a significant difference in the interaction effect between landmark type and the group on spatial knowledge acquisition is found, pointing out that wall objects may become more remarkable by displaying virtual landmarks in front of them, while 3D objects may require no further augmentation. However, a post-hoc analysis is required to confirm the statistical significance regarding this question. The results show no significant difference in the workload between the groups, but the NASA-TLX indicates a slight trend, suggesting that virtual landmarks can potentially increase the workload. Lastly, no evidence is found that participants who navigated with virtual landmarks felt more confident and experienced a lower stress level during the post-navigational questionnaires phase.

The proposed design demonstrates promising results for improving spatial learning and situational awareness when navigating an MR indoor environment. However, more studies, including eye-tracking, are required to analyze the user attention. This will help to optimize the design and hologram placement to maximize spatial learning acquisition and situational awareness. The potential limits of the workload should also be further analyzed.

Keywords: Wayfinding, Indoor Navigation, Virtual Landmarks, Augmented Reality, Mixed Reality, Workload, Microsoft HoloLens 2, Empatica E4

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List of Abbreviations

AECO	Architecture, Engineering, Construction, and Operation
AIC	Akaike Information Criterion
AR	Augmented Reality
BLE	Bluetooth Low Energy
EDA	Electrodermal Activity
FoV	Field of View
GIUZ	Geographisches Institut der Universität Zürich (Department of Geography of University of Zurich)
GLME	Generalized linear mixed-effects
glTF	Graphics Language Transmission Format
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
HMD	Head-mounted Display
IPIN	Indoor Positioning and Indoor Navigation
LM	Landmark
LME	Linear mixed-effects
LOD	Level of Detail
MR	Mixed Reality
NASA-TLX	NASA Task Load Index
PDR	Pedestrian Dead Reckoning
PPG	Photoplethysmography
RFID	Radio Frequency Identification
RV	Reality-Virtuality
SBSOD	Santa Barbara Sense of Direction Scale
SCR	Skin Conductance Response
SDT	Signal Detection Theory
SVG	Scalable Vector Graphics
UZH	University of Zurich
VL	Virtual Landmark
VR	Virtual Reality
XR	Extended Reality

1 Introduction

Daily, we depend on various navigation systems, including landmarks, wayfinding maps, and smart devices that use Global Positioning Systems (GPS) for indoor and outdoor wayfinding (Giudice et al., 2010; Hölscher et al., 2007; Yesiltepe et al., 2021). While these techniques are effective for outdoor navigation, there is still room for improvement in indoor navigation. In complex multilevel environments such as airports and hospitals, GPS signals fail to pass through walls because they get reflected by different materials, resulting in imprecise localization (Gu et al., 2009). Subsequently, this forces the navigation with landmarks, signs, and wayfinding maps within the building if no other alternatives (e.g. UZH now[1] a smartphone application with a location search function) are provided.

Indoor environments face two major challenges compared to outdoor navigation. The first problem refers to the difficulty of determining the user's location within the indoor environment, as Global Navigation Satellite Systems (GNSS) cannot be used effectively in indoor environments (Klinger, 2016). Secondly, digital models of buildings, which are essential for calculating the path to destinations within the building, do not exist or are not publicly available to everyone (Burkardsmaier and Sebastian Jansen, 2023).

According to (Technavio, 2024), the demand for Indoor Positioning and Indoor Navigation (IPIN) in different industries (e.g., retail, healthcare) is growing rapidly, and the IPIN market is expected to increase by USD 118.8 billion between 2023 and 2028. In general, indoor navigation systems can be classified into computer vision, communication technology, and pedestrian dead reckoning (PDR) (Kunhoth et al., 2020). Computer vision system extracts indoor environmental information with 3D cameras, while communication technologies work with radio frequency technologies such as Bluetooth Low Energy (BLE) beacon, Radio Frequency Identification (RFID) etc. The PDR utilizes accelerometers, gyroscopes, and magnetometer data to identify the user's position (Kunhoth et al., 2020; Subedi and Pyun, 2020). According to (Khan et al., 2022) vision-based methods are optimal solutions for indoor navigation because they are user-friendly, easy to implement, and require minimal costs compared to other methods.

The review of immersive technologies for indoor navigation (Sariman et al., 2024) also supports computer vision methods, highlighting that the future of indoor navigation lies in Extended Reality (XR) and navigation algorithms that define the current trend topics in indoor navigation systems. XR, including Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR) technologies, shows innovative ways that have the potential to improve indoor navigation where VR can be used to simulate complex indoor environments (Khan et al., 2020) and AR and MR can immerse the physical world with virtual objects to highlight objects and create navigation aids (e.g., holographic navigation arrows) (Mulloni et al., 2012). Furthermore, combining XR with deep learning and shortest-path algorithms in the future has the potential to enhance wayfinding even more, allowing different possible applications and use cases, for example, position-based evacuation scenarios, which would ensure the right

[1] https://www.zi.uzh.ch/de/students/software-elearning/mobile.html [04.09.2024]

decision-making and avoidance of dangerous hotspots (Sariman et al., 2024; Yoo and Choi, 2022).

1.1 Motivation and Aim

Although MR technology could improve indoor navigation, some limitations must be considered. Many studies indicate that there may be a trade-off between navigation performance and spatial knowledge acquisition when using automated navigation systems, with an increase in navigation performance and a decrease in spatial knowledge acquisition because human effort gets reduced (Brügger et al., 2019). Additionally, navigational aids can lead to divided attention, resulting in a worse spatial memory (Gardony et al., 2015). Furthermore, AR can reduce situation awareness and cause dangerous situations where the users get distracted from the real world and potentially walk into physical objects (e.g., doors, walls, people) or even fall while navigating on the stairs based on the examples reported using AR for outdoors (e.g., Pokémon Go) (Colley et al., 2017; Jung et al., 2018). Another essential negative aspect is that MR technology, such as Microsoft HoloLens 2, often requires a Head-Mounted Display (HMD), which can also worsen inattentional blindness (Krupenia and Sanderson, 2006).

Little research has been conducted on indoor navigation using different AR and MR tools to understand how humans perform in such environments (Kasprzak et al., 2013; Mulloni et al., 2012; Rehman and Cao, 2017). However, the question of how to design navigation aids in MR remains as (Liu et al., 2022) highlights that different visualizations of navigational aids can influence spatial learning, which is intensified by the fact that users tend to pay more attention to holographic arrows rather than their physical surroundings (Liu et al., 2021). Therefore, a research gap is present in finding the optimal design to ensure good navigation performance with minimal spatial knowledge acquisition loss and more situation awareness between the physical world and the MR environment. Furthermore, finding a specific design is only one part of the story because it is also essential to investigate how this design affects the user's workload during navigation to avoid an overload and provide design adaption possibilities (Armougum et al., 2019; Greenfeld et al., 2018; Kirsh, 2000).

There are many possibilities for designing a path for indoor navigation using holograms in MR. The study by (Lee et al., 2022) emphasize that users prefer arrows, avatars (human-looking tour guides), callouts (information boxes indicating directions), and desaturations (colored paths with a grey filter applied to the surroundings) during navigation. On the one hand, the customization of the hologram itself is important (Pfeiffer et al., 2021). For example, applying Bertin's visual variables on a single hologram, such as an arrow, creates many design variations that may influence the user's attention differently. This effect may be similar to the visualization of 2D maps, where some of Bertin's visual variables, such as size and color hue, are recognized much faster than others (Garlandini and Fabrikant, 2009). On the other hand, the path is also customizable and may influence the user experience during the navigation. For instance, navigation aids can be placed very close together or only at intersections, indicating that the position and amount of holographic navigation aids are important as well, as poor visualization can lead to misinterpretation or be overlooked during navigation (Liu et al., 2022).

In addition to these design techniques, the role of landmark-based orientation in wayfinding within indoor navigation is crucial because landmarks are often used as guidance for navigation (Deakin, 1996; Planning et al., 2008). *"Landmarks are defined as objects that contrast with the surrounding environment in terms of visual, semantic and structural aspects […]"* (Dong et al., 2019; Raubal and Winter, 2002). According to (Siegel and White, 1975), landmarks play a central role in human spatial representation because interacting with a new environment leads to acquiring landmark knowledge in the first stage. Therefore, it is important to consider the customization or highlighting of landmarks with holograms within the path created for navigation in the MR environment.

This study builds and continues the work of the Master's thesis by (Morf, 2022), which examined how to enhance spatial learning during navigation in an MR environment using Microsoft HoloLens 2. In his thesis, virtual text boxes were used to provide background information about physical landmarks to determine how this affects spatial learning during wayfinding. The results show that providing additional information on physical landmarks does not improve performance in spatial learning. However, the findings also indicate that the type of landmark is crucial, as 3D objects were remembered significantly better than other landmark types, such as signs and other wall features.

The main goal of this master's thesis is to experiment with a new design to enhance spatial learning and to increase situation awareness during indoor navigation using Microsoft HoloLens 2. The secondary goal is to provide insights into how this design affects the workload during navigation in the MR environment and the emotional stress when solving the post-navigational questionnaires.

1.2 Research Questions and Hypotheses

To address the goals of the study, the following research questions will be examined:

Research Question 1: Do virtual landmarks increase the awareness of the physical environment and enhance spatial learning during indoor navigation in MR?

Hypothesis 1: Integrating virtual landmarks as symbolic recreation in front of the physical landmarks for the MR indoor navigation environment enhances spatial learning compared to navigation with only physical landmarks.

Hypothesis 2: There is a significant difference in the effect of landmark type on spatial knowledge acquisition depending on whether virtual landmarks are displayed in front of physical landmarks.

Research Question 2: How does this design affect the workload while navigating in the MR environment and the emotional stress when solving the post-navigational questionnaires?

Hypothesis 3: The virtual landmark group has a significantly higher workload, indicated by the NASA-TLX than the group navigated without them.

Hypothesis 4: There is a significant difference in the average amplitude and the number of identified skin conductance response peaks during navigation between the group navigated with virtual landmarks and the group navigated without them.

Hypothesis 5: There is a significant difference in the average amplitude and the number of identified skin conductance response peaks when solving the post-navigational questionnaires between the group navigated with virtual landmarks and the group navigated without them.

2 Theoretical Background

2.1 Navigation and Spatial Knowledge

Navigation can be defined as "*coordinated and goal-directed movement through the environment by organisms or intelligent machines*" (Montello, 2005), which requires a combination of cognitive and motor abilities. He elaborates that cognitive abilities are responsible for recalling and understanding important environmental information, which is used to provide efficient movement through motor abilities. Navigation can be divided into two essential concepts, including locomotion and wayfinding.

Locomotion is related to navigation in the environmental surroundings, which are directly accessible by motoric impulses of the body. This navigation behavior includes avoidance of obstacles and navigation towards prominent landmarks in the area. In contrast, wayfinding focuses on efficient navigation to a specific destination point in the environment, located further away than the directly accessible surroundings, and requires decision-making and coordinated navigation (Montello, 2005).

To identify the current location and maintain orientation in the environment, two processes involving landmark-based and dead-reckoning are introduced (Montello, 2005). Landmarks can be characterized as visual (e.g., shape, color), semantic (e.g., historical relevance), and structural (e.g., key role in spatial environment) objects that attract the attention of people in the environment. Specifically, landmarks located at intersections are called local landmarks (Raubal and Winter, 2002). The landmarks can be used as reference points for the mental or cartographic map of the environment, which can help orient oneself in the environment and provide directions to the destination. On the other hand, dead-reckoning is based on the velocity and acceleration information, which is combined with the initial position and the time to calculate and update the current position in the environment (Montello, 2005).

The study of (Siegel and White, 1975), highlights that landmarks play an important role in human spatial representation because interacting with a new environment leads to acquiring landmark knowledge in the first stage. In the next step, the landmarks are used as reference points to acquire route knowledge, summarized as a sequence of direction changes at the specific landmarks. In the last stage, the distance between the landmarks is learned, resulting in a more detailed survey representation of the environment.

According to (Wiener et al., 2009), the wayfinding concept is more complex and can be further categorized based on the different wayfinding tasks respective to the knowledge levels (see Figure 1). The first layer of wayfinding consists of unaided and aided wayfinding. While aided wayfinding includes tools such as signs or maps that simplify the wayfinding task, unaided wayfinding does not feature any assistance support. However, depending on whether there is a destination point in the environment, unaided wayfinding can be classified into undirected and directed wayfinding. Undirected wayfinding is the exploration or navigation through an environment without specific intentions of reaching a particular destination. In contrast, directed wayfinding is based on reaching a specific destination and is classified into two further categories. The first category represents the search tasks using the available amount of survey knowledge about the environment without knowing the exact destination. An example could be looking for a friend in a restaurant, where the exact destination point of the friend is unknown, but the restaurant's location is known (informed search because survey knowledge of the area is available). The second example involves a firefighter looking for a person in a burning house (uninformed search because destination knowledge and survey knowledge of the area is unavailable). The second category is the target approximation, where the destination point is known. Depending on whether route knowledge and survey knowledge are available, the navigation along the path is adapted to reach the destination, resulting in categories including path following, path finding, path searching, and path planning.

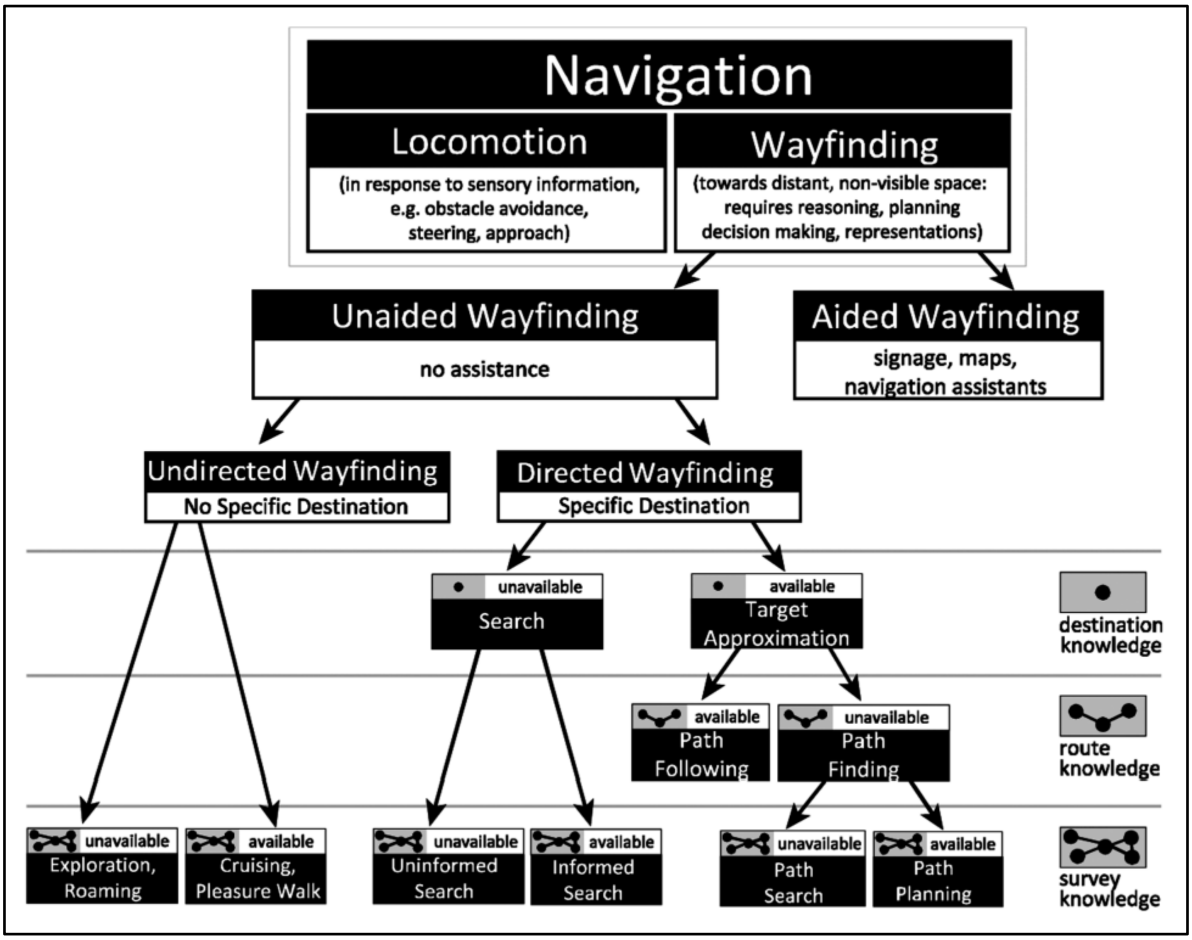


Figure 1: Wayfinding taxonomy based on wayfinding tasks (Wiener et al., 2009).

2.2 Mixed Reality

2.2.1 Definitions

To define Mixed Reality (MR), addressing the other terms related to this topic is essential. MR is a part of the Reality-Virtuality (RV) continuum, which ranges between two extremes. One side is limited by the real environment, which can be embedded with augmented elements visible through an augmented reality system (e.g., a display), ensuring a connection between the real world, where physical and augmented elements can coexist. In contrast, the other extremum is the virtual environment, which fully immerses the user in a simulated environment, creating an unawareness of the physical environment. Such simulated environments can mimic the real environment, be fictive, and be larger than the real environment in which the user is located. Subsequently, the MR environment can be defined as the environment that transitions between these two extrema of the (RV) continuum, blending the physical and virtual worlds (Milgram et al., 1995). According to (MILGRAM and KISHINO, 1994), there is a wide range of hybrid MR displays, including monitor-based non-immersive displays, immersive head-mounted see-through displays, and fully or partly immersive graphical displays. The Figure below shows an overview of the RV continuum with its key elements.

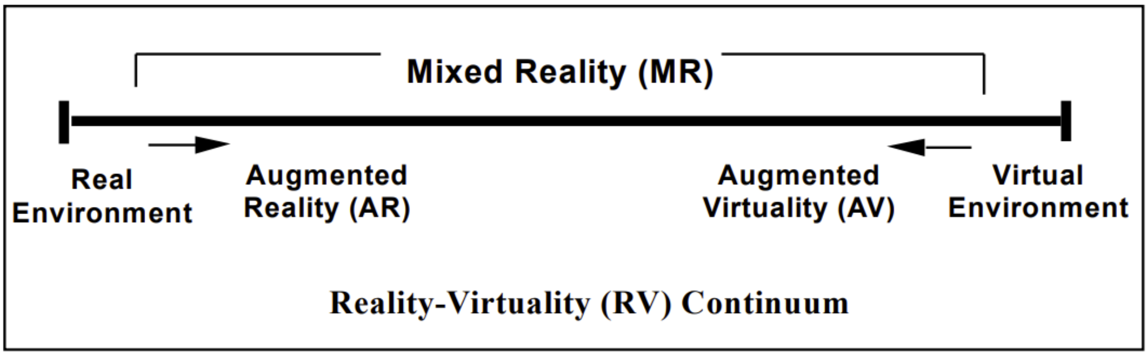


Figure 2: Overview of the Reality-Virtuality (RV) Continuum (Milgram et al., 1995).

2.2.2 MR Applications

The MR systems have become more advanced and popular nowadays, and therefore, many applications are developed for various industries, including architecture, engineering, construction, and operation (AECO) (Cheng et al., 2020). On the one hand, these applications can be used to visualize interiors, allowing customers to experiment with various designs and find an optimal solution for their specific use case (Vazquez et al., 2021). On the other hand, architectural elements such as building models can be visualized to better understand the construction process, ensuring efficient planning and communication (Assila et al., 2022). Another example of an MR application related to operation industries focuses on optimizing indoor navigation to simplify indoor wayfinding and improve operator time management (Neges et al., 2017). Apart from AECO industries, MR systems can offer a unique experience to explore and interact with a new environment (e.g., museum) (Chung et al., 2021; Hammady et al., 2020) or can help to enhance the learning experience in higher education (Banjar et al., 2023).

2.3 Indoor Navigation and Mixed Reality using HMDs

Apart from different applications presented in the previous chapter, MR and AR systems can also be used for indoor wayfinding, and many different studies have been conducted on this topic (Ng and Lim, 2020; Rehman and Cao, 2017). However, most studies focused on indoor navigation using mobile AR systems, which were very popular from 2012 to 2019 (see Figure 3). Nowadays, the HMDs AR devices seem to be gaining more popularity and set the current trends around this topic because they feature more advanced sensors related to AR and offer software development kits, which simplify the application development process (Cheliotis et al., 2023).

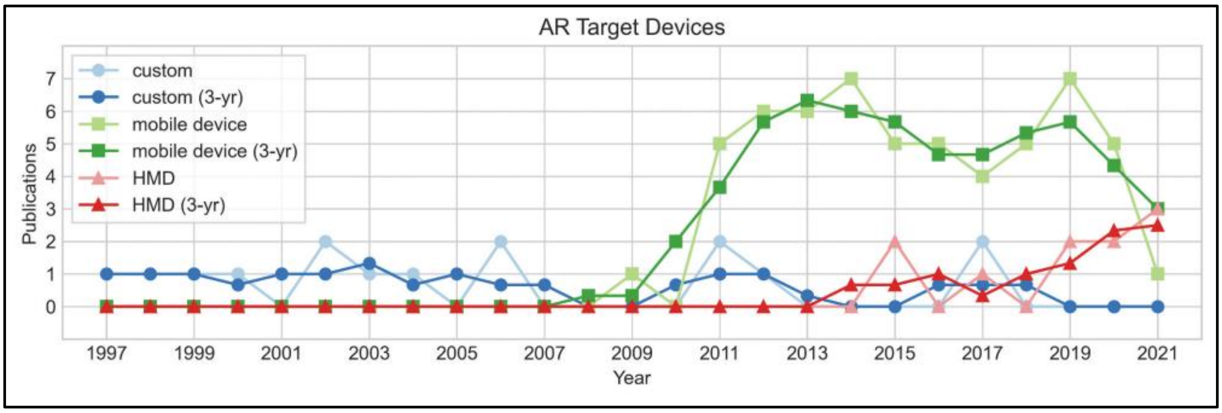


Figure 3: Number of studies by AR target devices over time (Cheliotis et al., 2023).

Little research has been done using the Microsoft HoloLens HMD for indoor navigation. The study by (Pfeiffer et al., 2021) emphasizes the importance of finding an optimal way to communicate navigation information to the user in an efficient way. They compared two visualization techniques by conducting an experiment using the HoloLens to analyze the mental workload and the time required for indoor wayfinding. The first design is based on displaying a holographic building layout map, which shows the user's current position and the destination point. The position on the map is updated continuously during the navigation. The second design utilized holographic arrows at intersections to indicate the turning direction. The study results show that using holographic arrows for navigation leads to a significantly lower mental workload than using a holographic building layout map, but no significant improvements regarding the time required to reach the destination are determined, which is explained by the fact that many participants experienced technical issues during navigation. However, the participants highlighted that they preferred the arrow design rather than the holographic building layout map. The study emphasizes that improvements to the design in terms of position, color, and size of the arrows should be further investigated in future work. Furthermore, it is unclear whether including additional augmented elements could improve indoor navigation.

Additionally, the study by (Zeman et al., 2022) addresses the issue of wayfinding inside the building during fire emergencies, which can have fatal consequences for firefighters. Therefore, the study suggests utilizing an HMD similar to Microsoft HoloLens 2 in the firefighter's helmet to ensure a more efficient way for navigation through the building to the fire position using the MR environment with holographic navigation aids, which can pop up and disappear dynamically during navigation. Besides navigation, the holographic elements could also display important information (e.g., hydrant positions).

Furthermore, the study by (Liu et al., 2021) highlight the problem of the lack of physical landmarks inside buildings. They conducted an experiment using the Microsoft HoloLens and showed that virtual semantic landmarks can be used to acquire incidental spatial knowledge during indoor navigation within MR. However, more research is required to understand the effectiveness of virtual landmarks and how their design and position may influence spatial learning during navigation. The study also points out that awareness of the physical environment is decreased while navigating with holographic arrows because users rely and focus too much on them rather than their surroundings. Another study by (Liu et al., 2022) reports that appropriate visualization design and position of navigation aids in MR is important, as unsuitable visualization can cause misinterpretation, influence spatial knowledge acquisition, and affect the mental workload during navigation.

To sum it up, the studies present different use cases and designs for indoor navigation in MR environments using the HMD Microsoft HoloLens device. However, further research needs to be done to explore new visualization designs of holographic navigation aids to enhance spatial learning and increase situational awareness of the physical environment during indoor navigation in the MR environment and to understand how these designs may affect the user’s workload.

3 Methods

A user study was conducted to address the previously introduced research questions. This chapter provides an overview of all essential aspects of the experiment and materials used in the study. First, the experiment aspects, including the experimental design, participants, the study area, and the route with its key elements, are introduced. Next, the material and tools are briefly explained. Lastly, the experiment procedure is described.

3.1 Experimental Design

In this study, a between-subject design was applied to investigate the impact of virtual landmarks on intentional spatial learning and the workload within the MR indoor navigation environment. It also examined whether this design affected the emotional stress during the post-navigational questionnaires phase. The 41 participants were divided into two groups:

Virtual Landmark Group (VL Group): Participants navigate with holographic arrows in the MR indoor environment, including virtual landmarks in front of the physical landmarks.

Control Group: Participants navigate with holographic arrows in the MR indoor environment without virtual landmarks in front of the physical landmarks.

The participants were evenly distributed between these groups based on their Santa Barbara Sense of Direction Scale (SBSOD) scores. Based on the provided consent form they knew that they would be guided with the help of MR assistance and that their spatial knowledge would be tested after the navigation task. However, they were not told about the specific design and the exact details that would be asked in the spatial knowledge tests.

The dependent variables for the study were spatial learning (measured with the Landmark Knowledge Test and the Route Knowledge Test in the post-navigational questionnaires), electrodermal activity (measured with the Empatica E4 wristband during the navigation task and the post-navigational questionnaires), and the NASA-TLX score (measured with the NASA-TLX iOS application). The independent variables were the visualization design for the MR indoor navigation (VL Group vs. Control Group) and the landmark type (3D objects vs. wall objects). Additional independent variables such as the SBSOD score, familiarity with the study area, and gender were collected from the pre- and post-navigational questionnaires and were also included in the analysis.

3.2 Participants

A total of 47 adults registered for the experiment via Google Forms[2]. There were no special requirements for participation in the experiment, except that the participants had to be healthy, around 18 and 65 years old, and have normal or corrected to normal vision (i.e., glasses or contact lenses). Participants could select a suitable slot for the experiment using a Doodle survey[3]. Three participants served as pilot testers to identify and resolve any issues,

[2] https://www.google.com/intl/en/forms/about/ [19.08.2024]
[3] https://doodle.com/ [19.08.2024]

ensuring that everything worked as intended during the experiment. Another three participants who registered for the experiment did not respond during the organization process and were excluded from the experiment, resulting in 41 participants. The average age of the participants was approximately 26.1 years, with a standard deviation of 4.7 years. There were 21 females (21-31 years) and 20 males (20-44 years). The figure below illustrates the age distribution among the participants. Most participants were students, people related to the GIUZ Institute, or friends. The route was designed so that the participants were less familiar with it. However, even when participants were familiar with the route, the familiarity effect was controlled for in the analysis, because this could influence the spatial knowledge acquisition (Ahmadpoor et al., 2019).

The participation in the study was entirely voluntary and did not incur any direct costs for the participants. The experiment lasted approximately 45 minutes. Apart from a small chocolate, there were no direct benefits or financial compensations for participating in the study. All information about the experiment procedure was provided in advance with a written consent form, giving the participants enough time to read it carefully at home to not waste much time during the experiment.

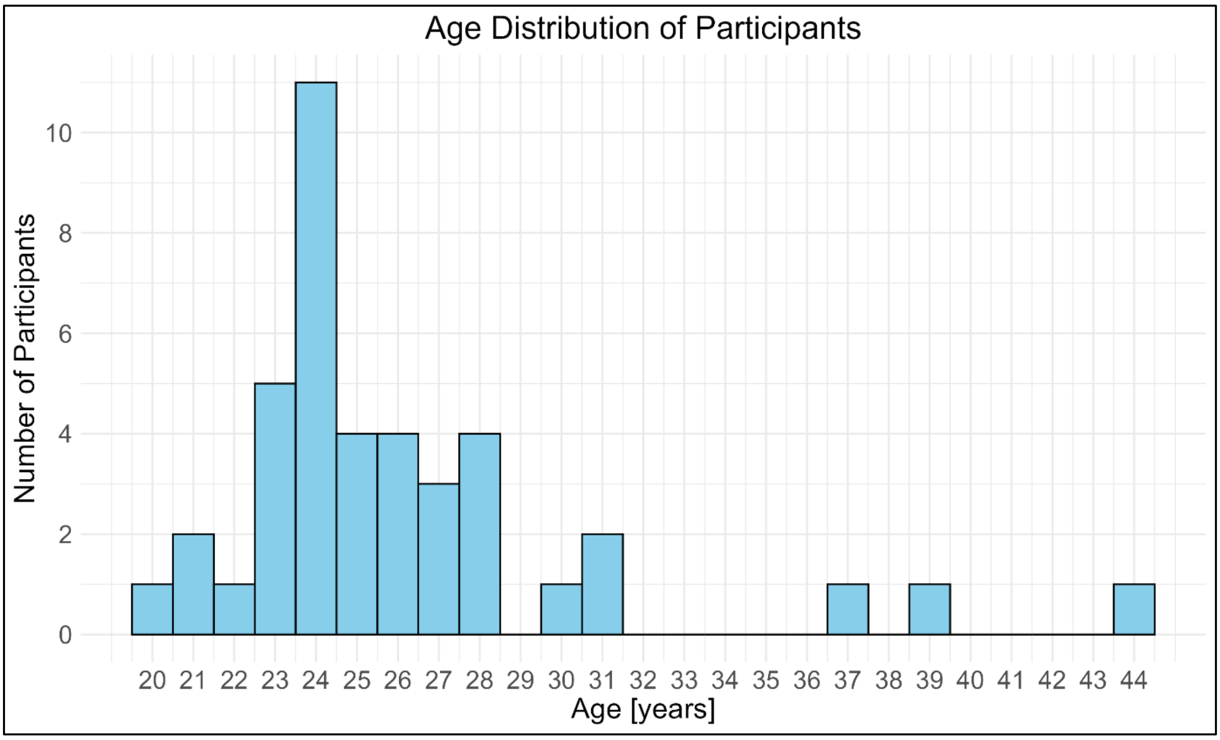


Figure 4: Distribution of participants' age.

3.3 Study Area

The experiment was conducted in the Irchel Campus of the University of Zurich (UZH)[4] (see Figure 5), consisting of more than 30 buildings, most connected by underground pathways. The multi-level complex structure of this building provides a variety of navigation possibilities, allowing the creation of a unique route for the indoor experiment. The advantage of this

[4] https://www.uzh.ch/cmsssl/de/explore/info/sites/irchel.html [19.08.2024]

building is that it is easily accessible for testing and troubleshooting and offers rooms for storing the equipment and conducting post-navigational questionnaires.

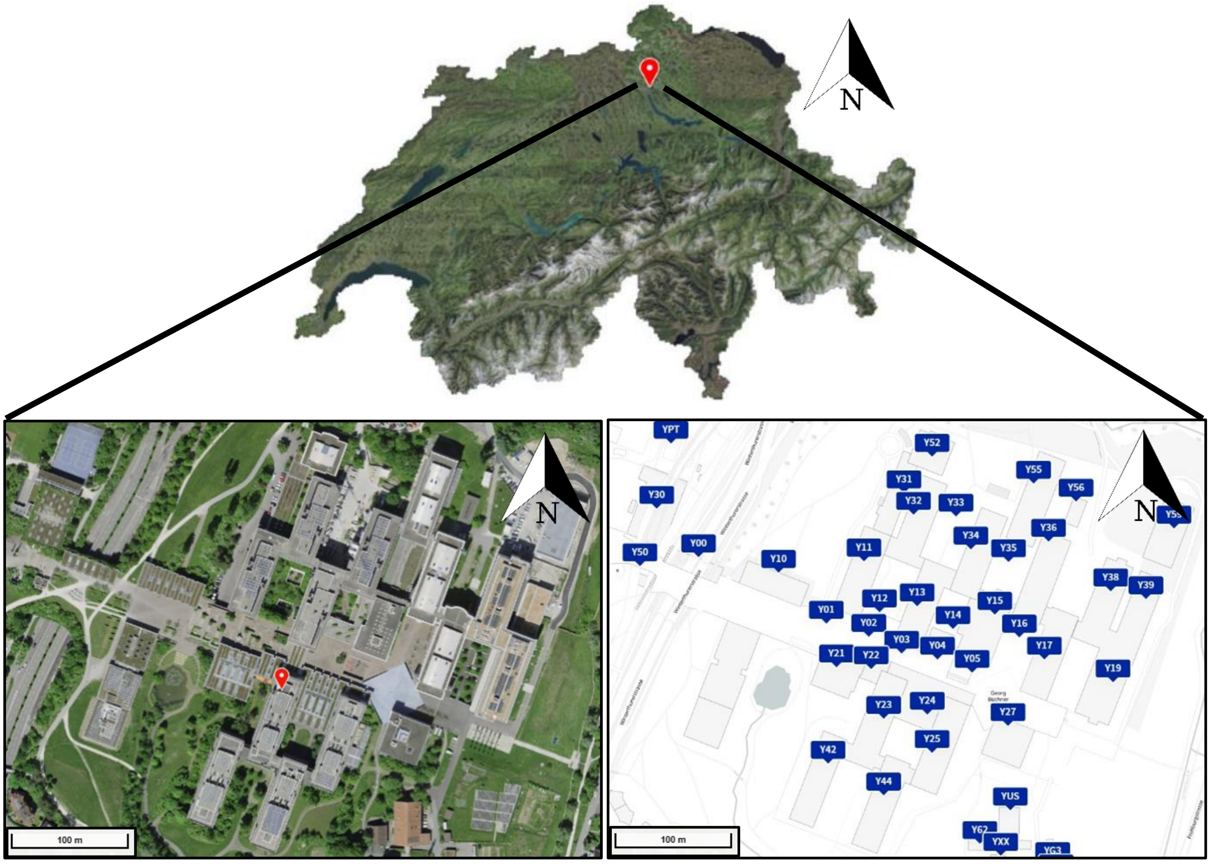


Figure 5: Study area in Zurich, accessed via map.geo.admin.ch & plaene.uzh.ch/campus/I [04.08.2024].

3.4 Route of the Experiment

The route leads through the Irchel Complex[5], including 24 buildings connected by underground pathways, except for a few unconnected buildings of the Irchel Campus. The participants navigated on three floors, F, G, and H, through the following buildings: Y55, Y35, Y15, Y16, Y36, Y17, Y38, Y34, Y13, Y14, Y03, and Y23. The route is approximately 525 meters long and has nine main intersections.

The route starts in front of the elevator on floor F of the neuroinformatic building (Y55), facing the emergency exit represented by room 121. From this point, the participant walks towards the emergency exit, turns left, and continues walking through the hallway until reaching the white staircase at the end. After ascending the white staircase, which leads to Y15 on floor G, the participant faces the white lockers built into the wall and then turns left. The next part involves walking straight, passing the physics exhibition on the right and a staircase on the left. After reaching the red-black round staircase in the Y38 building, the participant ascends to floor H and immediately turns left. In the next part of the route, the participant walks straight through a longer section. At the intersection indicated by the stairs on the right side, the participant will encounter a big plant and a bicycle parking area, visible through the window

[5] https://www.uniability.uzh.ch/static/control/info_display.php?structure=2143&rd_scrollY=300 [19.08.2024]

on the left side. Returning to Y15, now on floor H, the entrance to the University Library of Science can be seen on the left. Continuing moving forward, the participant passes another round staircase on the left side and a biology exhibition on the right, before arriving at the final round staircase, located in front of the internal post counter in Y13 on floor H. Using this round staircase to descend one floor, the Cafeteria Brunnenhof is briefly visible before the participant takes the round staircase one more time. After descending two floors, the participant is now in Y13 on floor F, facing a giant wall painting on the left side. Turning right towards the biology lab rooms, the participant walks forward, passing these lab rooms on the left and black lockers on the right, arriving at the Irchel 2050 exhibition. At the end of this section, there is a triangular-shaped sign on the wooden wall where the participant turns right and enters a wooden door leading to the Y03 corridor. After walking through this small section, the participant passes through a red door into a larger hallway on Y23 floor F. Moving towards the fire extinguisher installation on the left wall, the participant continues walking through three glass doors and then turns right at the physiology information board hanging on a brick wall. Finally, after turning right in front of the elevator, the participant reaches the end point of the route, located in front of the restroom Y23-F-7.

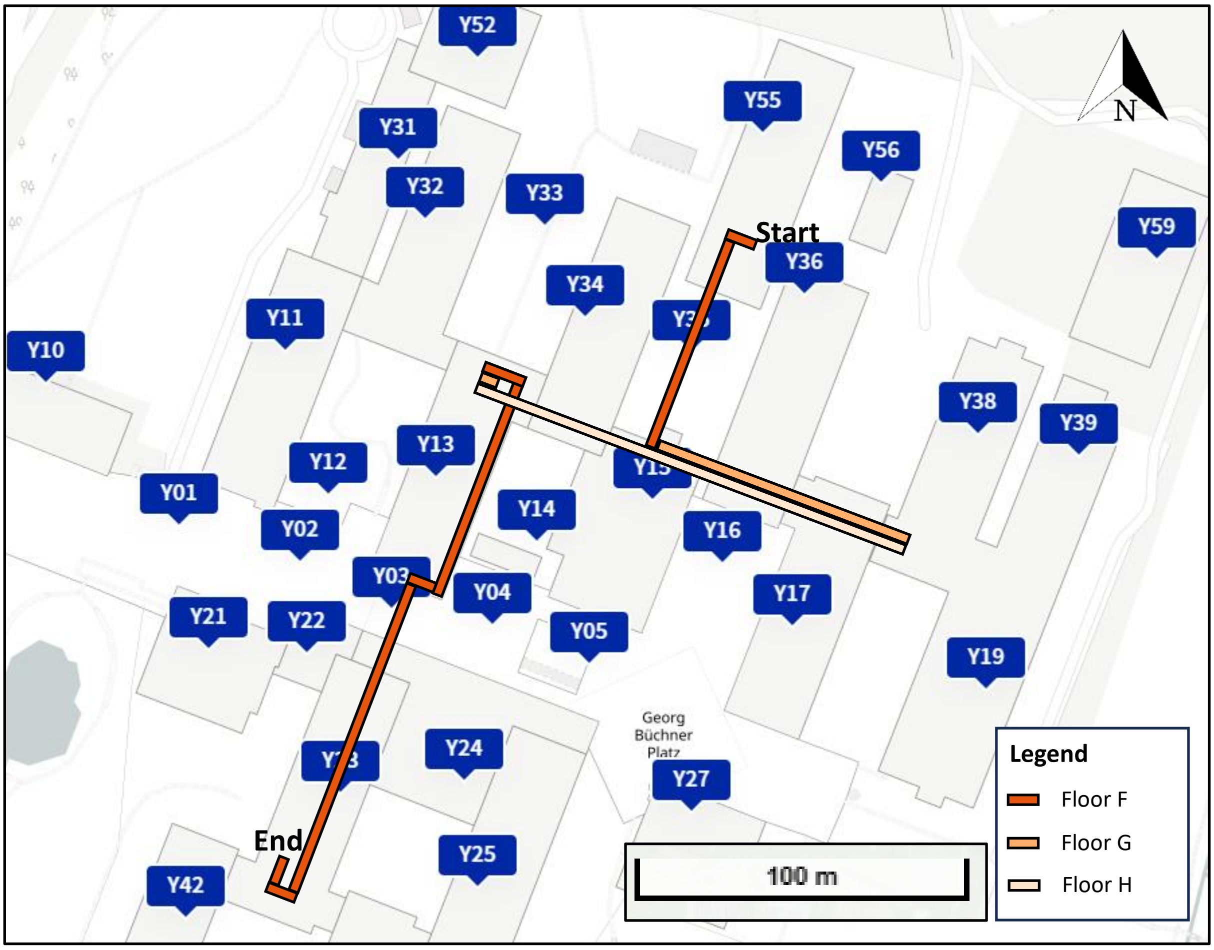


Figure 6: Route of the experiment, with floor F shown in dark orange, floor G in orange, and floor H in light orange.

3.5 Physical Landmarks

The route was designed in a way that it contains ten landmarks, which can be divided into two types: 3D objects and wall objects, with five of each type. The 3D objects represent salient 3D objects (e.g., a statue) and semantic locations (e.g., the cafeteria) in the study area. In contrast, wall objects are flat objects, such as signs, information boards, pictures, etc., that are either hanging on or built into the wall. Each landmark is located at a specific intersection and serves as a remarkable reference point for participants during the navigation. To test their ability to memorize the landmarks, ten additional landmarks (five of each type), that were not visible on the route during navigation were added in the Landmark Knowledge Test.

An overview of all twenty landmarks is presented in the table below. The landmark numbers have been randomized and do not appear in the same order in which the participants encountered them during the navigation. A more detailed description with an image of each landmark can be found in the Appendices.

Table 1: List of real and fake landmarks.

Landmark number	Description	LM type	Visible on route
LM1	3D mountain model	3D object	No
LM2	Information board	Wall object	No
LM3	3D chemistry model	3D object	Yes
LM4	Math workspace for students	3D object	No
LM5	Fire extinguisher	Wall object	Yes
LM6	Triangular wall sign (white)	Wall object	No
LM7	Coat rack stand	3D object	No
LM8	Large plant	3D object	Yes
LM9	Sand picture	Wall object	No
LM10	Campus Irchel 2050 exhibition	3D object	Yes
LM11	Information board	Wall object	Yes
LM12	Red round staircase	3D object	Yes
LM13	3D printed models exhibition	3D object	No
LM14	Three information displays next to each other	Wall object	No
LM15	Triangular wall sign (orange)	Wall object	Yes
LM16	Statue of Paul Karrer	3D object	No
LM17	White lockers built into the wall	Wall object	Yes
LM18	Cafeteria Brunnenhof	3D object	Yes
LM19	Red lockers built into the wall	Wall object	No
LM20	Giant wall art	Wall object	Yes

3.6 Virtual Landmarks

Another important aspect of the study includes the concept of the virtual landmarks. Virtual landmarks are holograms in the MR environment. They were used to highlight the physical landmarks by drawing the participant's attention away from the holographic arrows towards the physical landmark during the navigation task. All ten physical landmarks along the route were recreated as small symbolic virtual landmarks and positioned in front of the physical landmarks. This approach should ensure that participants create a connection between the virtual and physical landmarks, making physical landmarks more remarkable to enhance spatial knowledge acquisition and increase the awareness of the physical environment. It is important to note that these virtual landmarks were all stationary, slightly transparent, and did not include animated processes. A detailed explanation of how these holograms were created can be found in the “Hologram Creation” chapter. Figure 7 provides examples of physical landmarks with their corresponding virtual landmarks positioned in front of them. Note that the images were captured with the HoloLens, and the holograms appear brighter in the image than they were visible through the device during navigation.

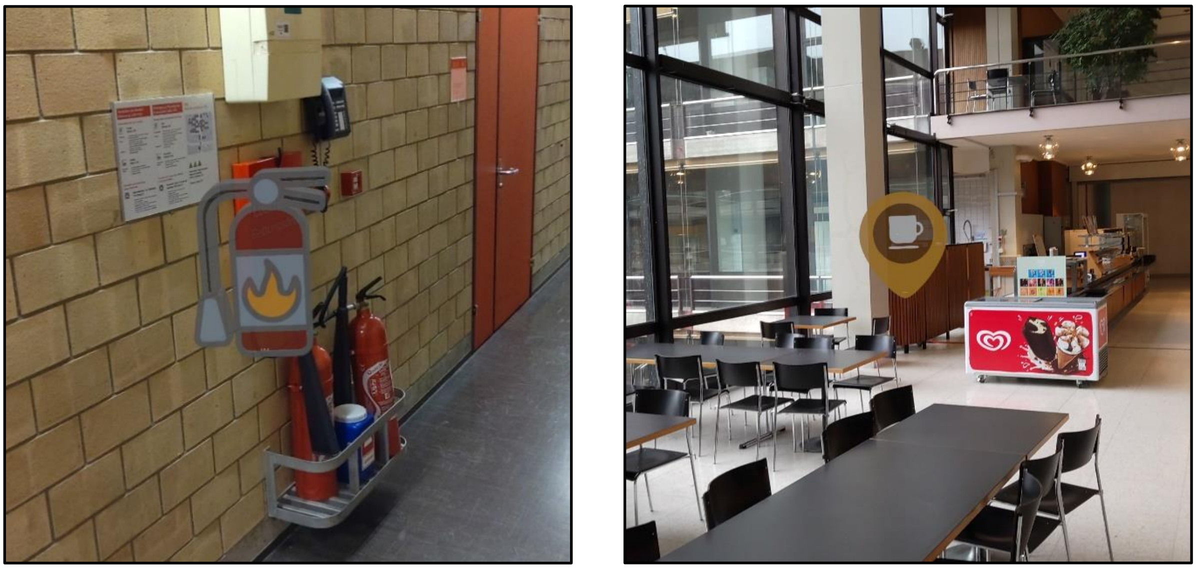


Figure 7: Visualization of virtual landmarks in front of their physical landmarks.

3.7 Intersections

The route consists of nine main intersections, which were identified by a unique landmark that served as a reference point for memorizing the correct turning direction. The route also has some intersections leading to lab rooms or outside the building. These intersections had no specific landmarks and were not included in the Route Knowledge Test. The direction the participant had to take was indicated by a holographic arrow in the MR environment (see Figure 8). All holographic arrows had the same size and were positioned approximately 1.5 meters above the ground at the intersection points. Participants were instructed that if no arrow was present on a specific section along the route, they should continue walking straight ahead.

Figure 8: Example of an intersection with virtual wall art in front of physical wall art and holographic arrows indicating the turning direction.

The table below provides an overview of all nine main intersections of the route with their corresponding landmarks. The intersection numbers have been randomized and do not appear in the chronological order in which the participants encountered them during the navigation. Note that intersection number two is a special case because two landmarks were placed in the same area close to each other. To avoid that, participants see the same intersection from different angles, both intersections from this area were combined into one in the Route Knowledge Test. The corresponding landmark used for the analysis was the last one encountered before leaving the area.

Table 2: List of nine main intersections on the route.

Intersection number	**Corresponding landmark**	**Approximate location**	**Possible directions**
1	LM20 (giant wall art)	Y13-F-90	down, straight, right
2	LM15 (triangular wall sign)	Y04-F-30	up, left, right
3	LM11 (information board)	Y23-F-13	left, right
4	LM18 (Cafeteria Brunnenhof	Y13-G-11	down, straight, right
5	LM5 (fire extinguisher)	Y23-F-64	straight, right
6	LM17 (white lockers built into the wall)	Y15-G-15	left, straight, right
7	LM3 (3D chemistry model)	Y13-H-01	straight, up, down
8	LM8 (big plant)	Y17-H-04	straight, up, down
9	LM12 (red round staircase)	Y38 floor G to floor H	left, right, up

The image below provides an overview of the entire route, with the position of each physical landmark visible during navigation, which indirectly indicates the main intersection points. The physical landmarks are represented by icons, which were used to create the virtual landmarks (as shown in Figure 7). Note that the three landmarks positioned next to each other are located on different floors.

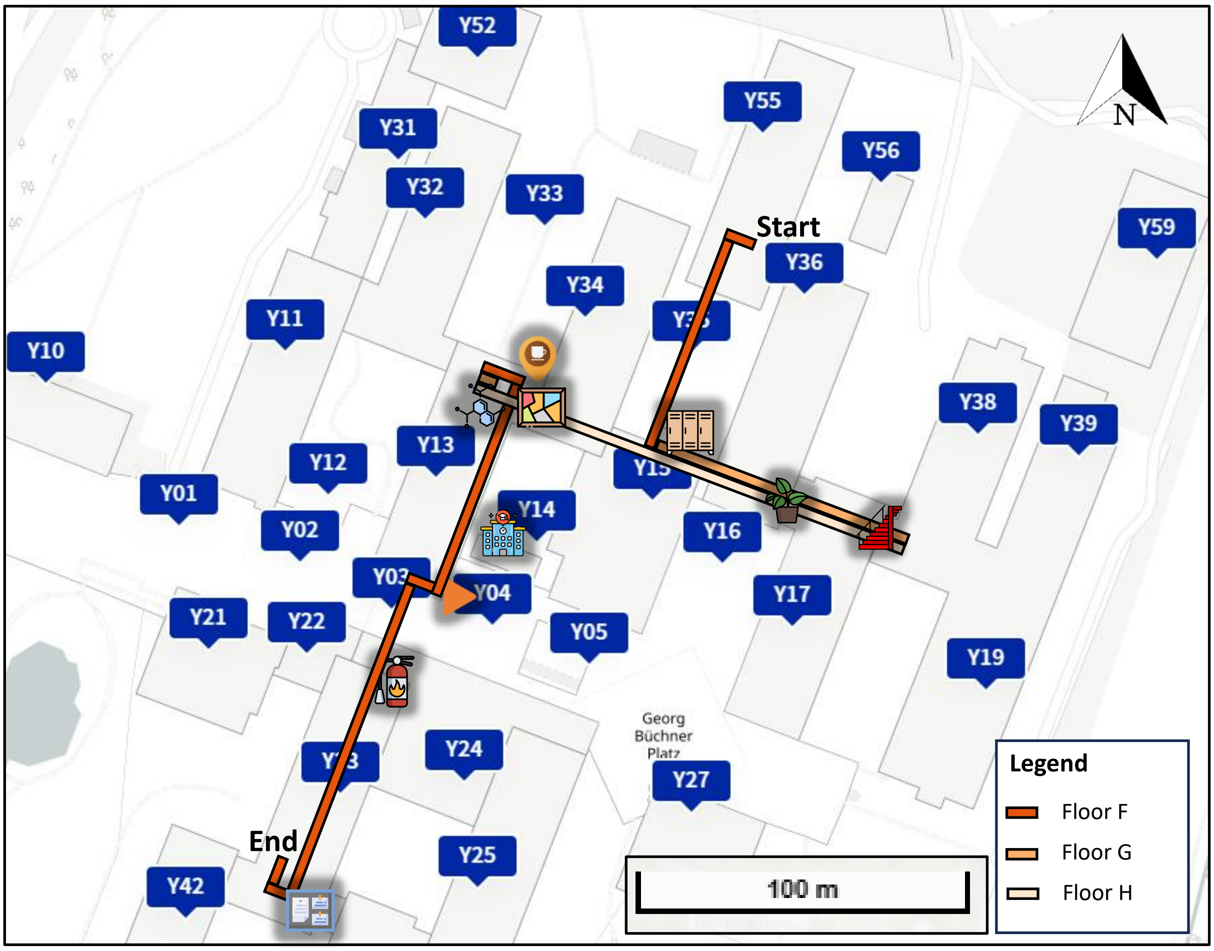


Figure 9: Route of the experiment with floor F in dark orange, floor G in orange, floor H in light orange, and physical/virtual landmarks as icons, indirectly indicating intersection points.

3.8 Materials and Tools

This chapter outlines the hardware and software used to conduct the study within the MR environment and to collect the data for the analysis. In the first part, the technical devices, including the Microsoft HoloLens 2 and the Empatica E4 wristband, are introduced. In the second part, the main data-collecting tools, such as the pre-and post-navigational questionnaires, are explained.

3.8.1 Microsoft HoloLens 2

The Microsoft HoloLens 2 is a mixed-reality HMD used to engage the participants within the MR environment during the navigation task of the experiment. The display consists of see-through holographic lenses with 2k resolution and an eye-based rendering optimization. The device has many advanced sensors, including visible light cameras for head tracking, two IR cameras for eye tracking, IMU, a depth sensor, and a camera (8-MP stills, 1080p30 video). Additionally, it can recognize hand tracking and voice commands, allowing human interactions. The device utilizes 6DoF tracking and spatial mapping technology to understand and map the environment in real-time ("HoloLens 2—Overview, Features, and Specs | Microsoft HoloLens," n.d.)

There are different ways to integrate holograms into the Microsoft HoloLens 2. One option is the LandMarkAR application on the HoloLens, a tool developed in the context of a Master's thesis by (Luchsinger, 2023), specifically for research purposes in MR indoor navigation environments. This application serves as a playground tool for designing navigation projects. The advantage of the application is the ability to create multiple projects at once, which is very useful for between-subject design experiments. Additionally, it includes features such as selecting pre-uploaded holograms or importing (.gltf) files and allows easy positioning by moving and rotating them in the environment. However, the application has an issue saving the hologram positions to the Microsoft Azure cloud and could not be used in this study. The alternative approach involves using the Microsoft 3D Viewer application on the HoloLens, which saves the hologram positions by creating a mental map using the HoloLens' 6DoF tracking and spatial mapping sensors. The disadvantage of this method is that the study supervisor must manually design the holographic arrows at the correct angle for the environment. Additionally, the application is not suitable for creating multiple projects simultaneously. This requires all participants from one group to complete the experiment before the visualization can be adjusted for the next group, which can lead to logistics problems during the organization.

Besides engaging participants within the MR environment, the HoloLens was also used to capture the visual content displayed during navigation for analysis purposes. However, no video or photographic recordings of the participants themselves were made.

3.8.2 Hologram Creation

There are many online resources available to download assets for MR environments (e.g. Free3d[6], open3dmodel[7]). However, many of these assets are not free and require a paid subscription. Sometimes, assets must be purchased individually, which can become very expensive. Another issue is that the design of the assets may not fit the environment or vary significantly between different assets, making it difficult to maintain a uniform design for all virtual landmarks. Additionally, finding digital representations of each physical landmark can be challenging. To avoid these issues, the virtual landmarks were created using the free modeling software Blender (Community, 2018).

To simplify the modeling process, flat icons and symbols were used as a starting point. The advantage of this approach is that there is a wide range of icons and symbols for specific topics that can be easily found on different online platforms. For this study, the icons from the online platform Flaticon[8] were used. After downloading the icons as scalable vector graphics (.svg) and importing them into Blender, the flat icons were extended into 3D objects and exported as graphics library transmission format (.gltf) files, which is a suitable format for MR environments. The 3D models were then copied to the HoloLens and accessed via the 3D Viewer application (Lolambean, 2022).

A few things must be considered during the modeling process. An icon is created of several overlapping layers, each responsible for a specific detail of the icon. The layers cannot share the same Z-coordinate in Blender, as this causes a rendering issue called Z-fighting because the software is not able to understand which layer should be rendered first (Vasilakis and Fudos, 2013). To solve this problem, the thickness of each layer must be slightly increased, starting from the background layer, followed by all detail layers, and finishing with the contour lines layer, which has the greatest thickness. This ensures that each layer has a different Z-coordinate in chronological order, preventing Z-fighting from occurring. One tool that can be used to do this in Blender is “extrude” (“Geometry — blender manual,” n.d.). Additionally, specific layers representing shadows on the icon must be removed to give the 3D model a more natural appearance.

Another important aspect is that each layer consists of a mesh. A mesh is a collection of faces, vertices, and edges, creating an object (“Glossary — Blender manual,” n.d.). Faces can be subdivided into smaller pieces of triangles (“Subdivide — Blender manual,” n.d.). The number of mesh objects can be viewed in the statistics table, including the number of vertices, faces, triangles, or bones. The more complex a shape is, the more triangles it contains, which must be considered when creating assets. At the final stage of the creation process, some icons must be simplified by joining all layers into one and reducing the number of triangles using a “decimate modifier” (“Clean up — blender manual,” n.d.) before exporting and copying them to the HoloLens.

The simplification process is necessary due to the launcher application requirements (Lolambean, 2022; BrandonBray, 2022) limiting the level of details (LODs) to a maximum of

[6] https://free3d.com/ [20.08.2024]
[7] https://open3dmodel.com/ [20.08.2024]
[8] https://www.flaticon.com/ [20.08.2024]

10,000 triangles per hologram loaded into the 3D Viewer application on HoloLens 2 (Vtieto, 2022). If this limit is exceeded, the holograms will not be displayed.

The images below provide an example of Z-Fighting with the statistic table and the process of creating a virtual landmark.

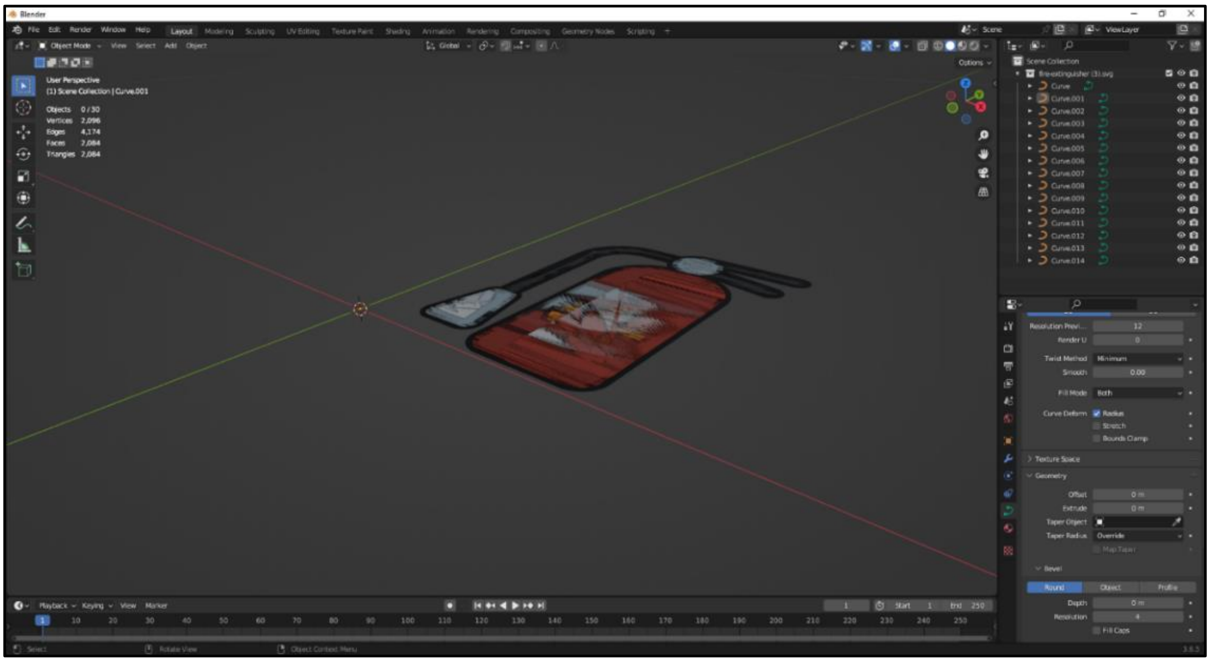


Figure 10: Z-fighting of SVG layers in the fire extinguisher icon.

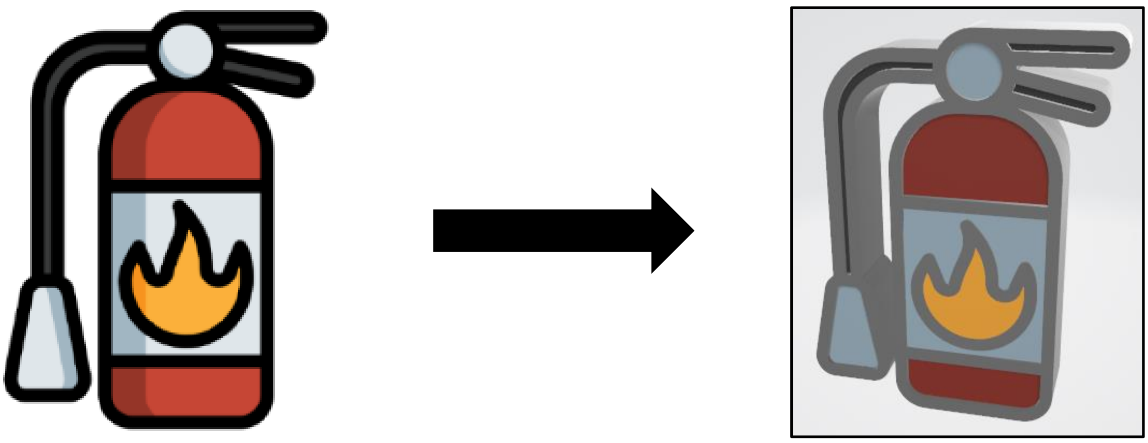


Figure 11: Creating a virtual landmark (simplified process).

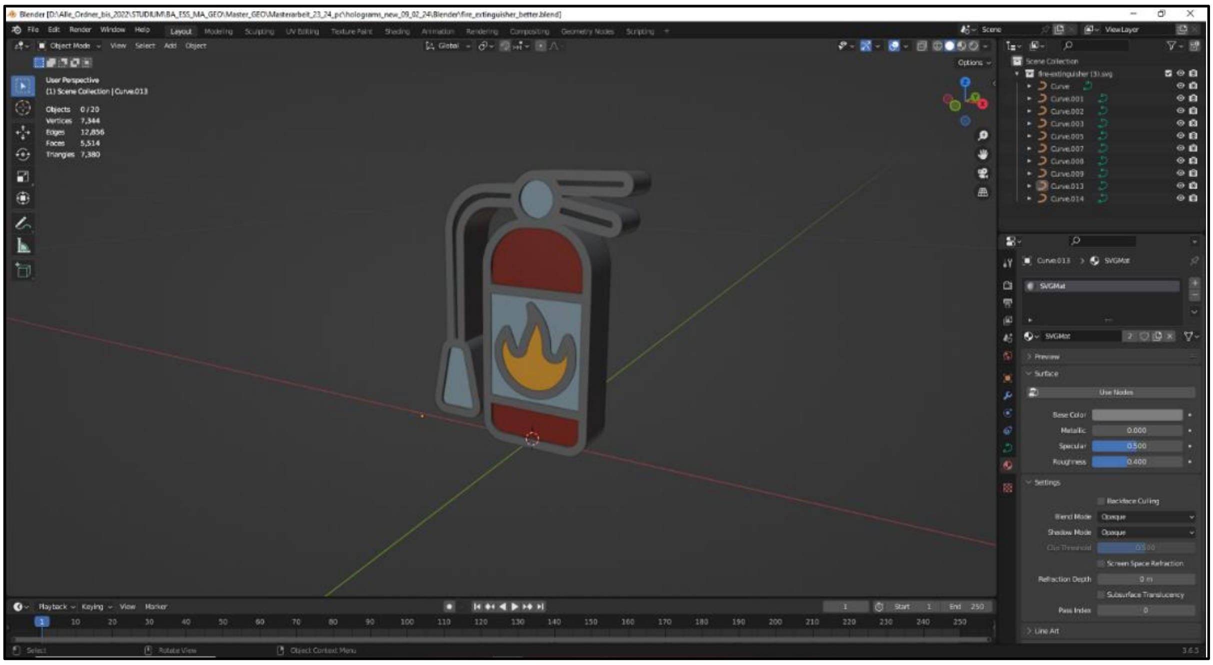


Figure 12: Process of creating a virtual landmark in Blender.

The start and end point holograms contain a lot of text and can be considered complex geometric shapes due to the various curves in the letters. In this case, the decimation approach will not work because the letters would lose their original shape and become unrecognizable. This problem can be resolved by creating a text texture and applying it to the hologram. To achieve this, the free online tool Canva[9] was used to create a background image with the start and end text for the holograms. After downloading the image, it was imported into a simpler design and editing application called 3D Builder[10], where it was edited using the “Contour” method. The parameters, including Layers, Smoothness, Texture, and Inversion, were adjusted until the texture looked good. Finally, the completed hologram was transferred to the HoloLens, where it could be opened with the 3D Viewer application.

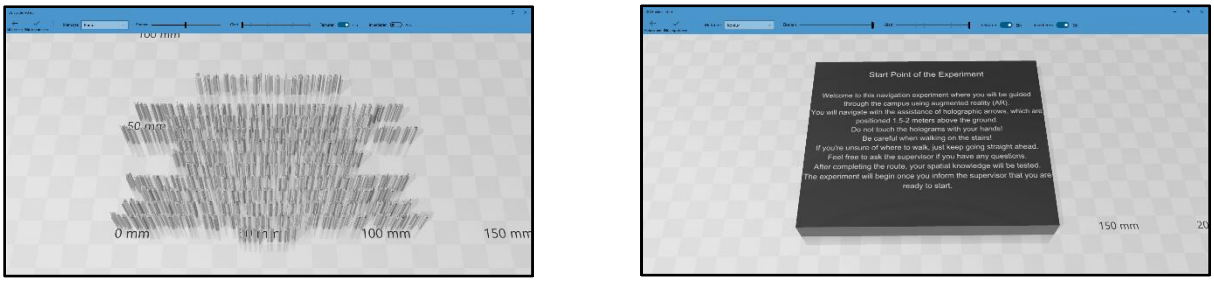


Figure 13: Process of creating a text hologram in 3D Builder.

[9] https://www.canva.com/ [20.08.2024]
[10] https://3d-builder.en.uptodown.com/windows [20.08.2024]

3.8.3 Empatica E4 Wristband

The Empatica E4 is a wristband the participants wore during the entire experiment. It was used to monitor the physiological parameters, which indicated the emotional state of the participant for each part of the experiment. The device features advanced sensors, including the photoplethysmography sensor (PPG) used to measure the blood volume pulse, the 3-axis accelerometer, which captures movement activity to analyze movement patterns, the infrared thermopile sensor to measure the peripheral skin temperature, and the electrodermal activity sensor (EDA) to measure the skin conductance changes caused by sweat glands at the wrist indicating sympathetic nervous systems arousal which can be used to derive emotional states, such as stress and excitement levels. It also has an event mark button for tagging specific events during the measurement session ("Real-time physiological signals - E4 EDA/GSR sensor," n.d.) To record the session, the device was connected via Bluetooth to the E4 realtime[11] application on the smartphone. The data was then stored and uploaded to the supervisor's account on the E4 connect[12] server, where it could be reviewed and downloaded. Following a similar approach to the study by (Armougum et al., 2019), the essential sensor used to identify emotional stress and mental workload through physiological data was the EDA sensor. The data recorded from the other sensors was available as well but was not included in the analysis. The wristband recorded the data during the entire experiment session, including the navigation task and the post-navigational questionnaires.

3.8.4 Questionnaires

The participants were asked to complete six different questionnaires, which can be categorized into pre- and post-navigational questionnaires. The pre-navigational questionnaires included the Experiment Registration Form and the SBSOD. The post-navigational questionnaires included the Landmark Knowledge Test, Route Knowledge Test, NASA-TLX test, and the Final Questionnaire. All questionnaires except NASA-TLX were created and conducted using the free online tool Google Forms. Participants had no time limit and were only allowed to ask questions during the NASA-TLX test. Since it was not possible to display each question on a separate page using Google Forms, the participants were instructed to fill out the questions in chronological order without going back to revise the previous answers.

3.8.5 Experiment Registration Form

Interested participants registered for the experiment through a Google Forms registration form. The form collected participants' demographic and contact information, including full name, age, gender, email, and phone number. This information was essential for organizing the experiment and communicating important details, such as the consent form and available time slots, to the participants.

[11] https://play.google.com/store/apps/details?id=com.empatica.e4realtime [20.08.2024]
[12] https://e4.empatica.com/connect/login.php [20.08.2024]

3.8.6 Santa Barbara Sense of Direction Scale

The SBSOD test was used to assess participants' spatial abilities and orientation skills and was conducted immediately after the experiment registration, before the actual experiment, to obtain each participant's score. Based on these scores, participants were evenly distributed between the two study groups, ensuring that both groups included participants with high and low orientation abilities. This distribution was crucial to prevent one group from outperforming the other due to a potential imbalance of participants with good orientation skills in one group. The test consists of 15 self-report statements about spatial and navigational abilities, preferences, and experiences. Participants rated their sense of direction by indicating their level of agreement with each statement using a Likert scale, ranging from 1 (strongly agree) to 7 (strongly disagree). To calculate the SBSOD score the average across the 15 statements was taken. However, before calculating the average, statements 1,3,4,5,7,9, and 14 require reverse scoring because they are positively worded. This means that a response of 1 is recoded to 7, 2 to 6, and so on. The final score ranges from 1 to 7, with 1 representing a poor sense of direction and 7 representing an excellent sense of direction (Hegarty et al., 2002).

The first three statements of the SBSOD are presented in the table below. The full version of the test can be found in the Appendices.

Table 3: First three statements of SBSOD.

Statement	Level of agreement
1. I am very good at giving directions.	1 (strongly agree) to 7 (strongly disagree)
2. I have a poor memory for where I left things.	1 (strongly agree) to 7 (strongly disagree)
3. I am very good at judging distances.	1 (strongly agree) to 7 (strongly disagree)

3.8.7 Landmark Knowledge Test

In the Landmark Knowledge Test, participants were presented with images of landmarks and asked to indicate whether they had seen them while navigating the route. A total of 20 landmark images were shown, but only 10 were visible during the navigation. These additional 10 fake landmarks were used to measure how well participants could distinguish between real and fake landmarks. The images were cropped to limit the view of the surrounding area to ensure that the landmark was not easily recognizable. Participants had to decide whether they saw the landmark during the navigation by selecting one of the options: “Yes, I saw this Landmark” or “No, I did not see this Landmark.” The images were randomized and did not appear in the same order in which the participants might have encountered them during the navigation. Additionally, participants were asked to rate how confident they were in their answers for each landmark on a scale from “1 (Very unsure)” to “5 (Very sure)”.

Below is a snippet of the Landmark Knowledge Test. The images of each landmark and the complete Landmark Knowledge Test can be found in the Appendices.

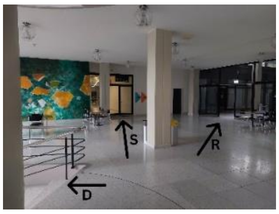
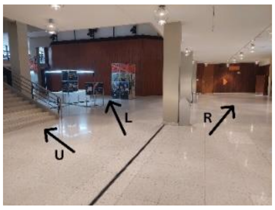
Table 4: Snippet of the Landmark Knowledge Test.

Question	Answer Possibilities
Participant ID (The study supervisor will enter this information for you. No input required.)	
Landmark 1 	Yes, I saw this Landmark. No, I did not see this Landmark.
Landmark 1: Please indicate how confident you are in your answer.	1 (Very unsure) to 5 (Very sure)
…	…
Landmark 20 	Yes, I saw this Landmark. No, I did not see this Landmark.
Landmark 20: Please indicate how confident you are in your answer.	1 (Very unsure) to 5 (Very sure)

3.8.8 Route Knowledge Test

In the Route Knowledge Test, participants were presented with images of intersections and asked to indicate the direction they took at each intersection. A total of nine intersection images were presented. The intersections were shown from the same angle encountered during navigation and included the physical landmarks. The possible directions were indicated by arrows in the image. Participants had to decide whether they turned left, right, continued straight, or moved up or down by selecting one of the options: "L (Left)", "R (Right)", "S (Straight)", "U (Up)", or "D (Down)." The images were randomized and did not appear in the chronological order in which the participants may have encountered them during the navigation. Additionally, participants were asked to rate how confident they were in their answers for each intersection on a scale from "1 (Very unsure)" to "5 (Very sure)". Other methods for testing the route knowledge such as asking participants to return to the starting point or sketching the route on paper (Rovine and Weisman, 1989; Wiener et al., 2024) were also considered. However, these approaches are more complex and would have exceeded the one-hour session per participant, making them unsuitable for the study. The table below presents a snippet of the Route Knowledge Test. The images of each intersection and the complete Route Knowledge Test can be found in the Appendices.

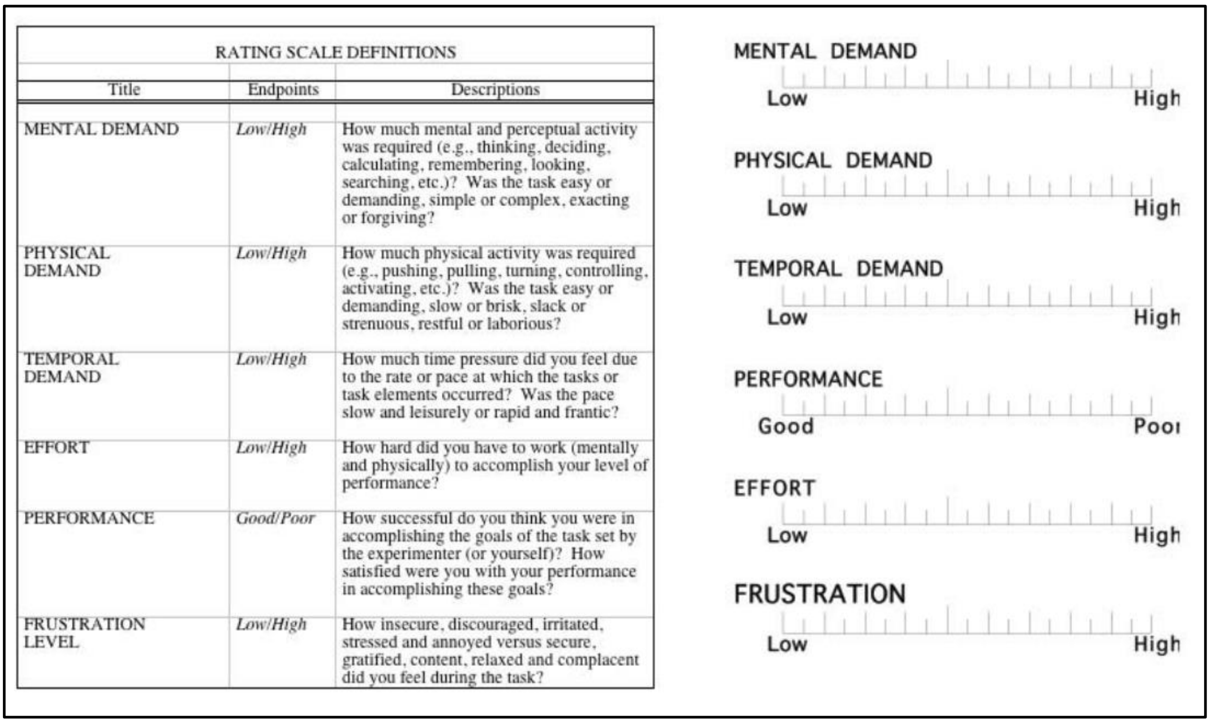
Table 5: Snippet of the Route Knowledge Test.

Question	Answer Possibilities
Participant ID (The study supervisor will enter this information for you. No input required.)	
Intersection 1 	D (Down) S (Straight) R (Right)
Intersection 1: Please indicate how confident you are in your answer.	1 (Very unsure) to 5 (Very sure)
Intersection 2 	U (Up) L (Left) R (Right)
Intersection 2: Please indicate how confident you are in your answer.	1 (Very unsure) to 5 (Very sure)

3.8.9 NASA Task Load Index Test

The NASA-TLX test was conducted with the NASA-TLX iOS application[13]. It is based on a multi-dimensional scale to evaluate the task workload and can be performed either during or immediately after the task. In this study, the test was conducted after the navigation task. The workload is defined by six subscales, including Mental Demand, Physical Demand, Temporal Demand, Performance, Effort, and Frustration. Participants rated their experience on each subscale separately on a scale from low to high, corresponding to numerical values from 0 to 100 (see Figure 14). There are different methods for calculating the workload. One example is the weighted workload, where participants are presented with additional questions with pairs of the six subscales and must choose which factor is more important to their workload experience. This information is then used to weight the subscale ratings. The advantage of this method is that it increases the sensitivity and reduces the variability between participants. Other methods include analyzing the subscale individually or calculating the mean of the sum of all subscales, excluding the weighting process (Hart, 2006; Hart and Staveland, 1988). Due to time limitations, the weighting process was excluded, and the mean of the sum of all subscales was used in this experiment. The NASA-TLX Test can be found in the Appendices.

[13] https://humansystems.arc.nasa.gov/groups/TLX/tlxapp.php [20.08.2024]



RATING SCALE DEFINITIONS

Title	Endpoints	Descriptions
MENTAL DEMAND	Low/High	How much mental and perceptual activity was required (e.g., thinking, deciding, calculating, remembering, looking, searching, etc.)? Was the task easy or demanding, simple or complex, exacting or forgiving?
PHYSICAL DEMAND	Low/High	How much physical activity was required (e.g., pushing, pulling, turning, controlling, activating, etc.)? Was the task easy or demanding, slow or brisk, slack or strenuous, restful or laborious?
TEMPORAL DEMAND	Low/High	How much time pressure did you feel due to the rate or pace at which the tasks or task elements occurred? Was the pace slow and leisurely or rapid and frantic?
EFFORT	Low/High	How hard did you have to work (mentally and physically) to accomplish your level of performance?
PERFORMANCE	Good/Poor	How successful do you think you were in accomplishing the goals of the task set by the experimenter (or yourself)? How satisfied were you with your performance in accomplishing these goals?
FRUSTRATION LEVEL	Low/High	How insecure, discouraged, irritated, stressed and annoyed versus secure, gratified, content, relaxed and complacent did you feel during the task?

Figure 14: SBSOD subscales definitions and the rating scale (Hart, 2006).

3.8.10 Final Questionnaire

The Final Questionnaire was used to assess participants' familiarity with the route, their experience with MR, and their comfort level while navigating the route using the HoloLens. The questions were asked in the form of a Likert scale, and participants were asked to rate their agreement on a scale from 1 (strongly disagree) to 5 (strongly agree). At the end, the participants also had the opportunity to provide any feedback in an open-ended question. The Final Questionnaire can be found in the Appendices.

3.9 Procedure

Before conducting the main study, three participants were used for pilot tests to ensure that everything worked as intended and to improve the study design if required. The pilots were similar to the main study, with only a few minor changes, which included shortening the route due to technical issues.

The main study consists of three parts:

The first part took place prior to the actual study. The participants were asked to register via Google Forms and provide basic information about themself (e.g., age and gender). Next, the participants completed the SBSOD, which was used to identify the spatial skills and orientation in space (Hegarty et al., 2002). To control for this parameter in the analysis, participants with high and low SBSOD scores were evenly distributed between the study groups.

The second part of the experiment was the navigation task, which was conducted using the Microsoft HoloLens 2. Each participant was individually met outside near the blue cow statue in front of the entrance of the Y13 building. The participant was then guided to the starting point. At the starting point, the experiment procedure was briefly repeated, and the participants were asked to sign the consent form, which had been provided in advance to give them enough time to read it carefully at home. In the next step, the Empatica E4 wristband was installed on the non-dominant hand and calibrated by instructing the participant to sit with eyes closed while wearing ear protection and relaxing for two minutes. A similar method was used in the study by (Campanella et al., 2023). This approach was necessary to establish a baseline and ensure that the participant was at a neutral emotional level. The Microsoft HoloLens 2 also had to be calibrated to the participant's eyes to ensure precise positioning of holograms. After calibration, the safety instructions for the navigation task were explained. Lastly, the video recording was started to capture the visual content displayed on the HoloLens for later analysis, and the participant was guided to the first hologram (start point hologram). This was the last opportunity to ask questions. For the next approximately eight minutes, the participant was guided through the Irchel Complex using MR assistance. The supervisor followed a few meters behind, without interaction, unless the participant made a wrong turn or technical issues occurred. Reaching the endpoint of the navigation, the video recording was stopped, and the participant was guided to the eye-tracking lab for the final part of the experiment.

In the third and final part of the experiment, the participant completed the post-navigational questionnaires, including the Landmark Knowledge Test, Route Knowledge Test, NASA-TLX Test, and the Final Questionnaire. After completing the questionnaires, the Empatica E4 recording was stopped, and the participant received a small chocolate as compensation for participating in the study. During the experiment, the time stamps for the navigation task and the questionnaires were logged using the aTimeLogger[14] application on the smartphone to identify the specific timeframes of the EDA recording corresponding to each part of the study.

3.10 Data Analysis

The open-source software RStudio (Posit team, 2023) was used for data processing, statistical testing, and visualization of the results. Additionally, EDA Explorer, a software designed by (Taylor et al., 2015), was utilized to analyze the EDA data and detect peaks indicating emotional arousal. The software code was provided on GitHub[15], allowing modifications and extensions to improve the analysis. The analysis process is divided into two parts. The first part addresses spatial learning and tests hypotheses H1 and H2, while the second part focuses on task workload and emotional stress, including hypotheses H3, H4, and H5.

In the first part, the data obtained from the questionnaires were merged, split into landmark and route knowledge data, and transformed into a long format. The landmark knowledge test, simplified to a yes-no task with two possible stimulus types, was analyzed using the Signal Detection Theory (SDT), which describes the ability to distinguish between signal and noise (Stanislaw and Todorov, 1999; Tanner and Swets, 1954), essentially how decisions are made under conditions of uncertainty (Senior et al., 2015). This corresponds to the participant's ability to differentiate between real landmarks encountered during navigation (signals) and

[14] https://atimelogger.pro/ [20.08.2024]
[15] https://github.com/MITMediaLabAffectiveComputing/eda-explorer [20.08.2024]

landmarks that were not present on the route (noise). Following that, a yes response to a signal is equivalent to a hit, while a yes response to noise is defined as a false alarm (Stanislaw and Todorov, 1999) and so on (see table below). To calculate the SDT indices, including the d-prime value, which is computed as z(hit rate) minus z(false alarm rate), the “dprime” function of the psycho package (Makowski, 2018) in R was used. The function requires a few parameters, including the number of hits, false alarms, misses, correct rejections, targets, and distractors, which can be calculated from the obtained data. The determined d-prime score for each participant allows for a comparison of the performance between the two groups (VL Group vs. Control Group). The same method was applied to the landmark types and tested the participant's ability to distinguish between real and fake 3D objects, as well as between real and fake wall objects, within both groups. The d-prime value was used as a dependent variable in a linear mixed-effects (LME) model.

However, SDT cannot be applied to the route knowledge data because this test did not involve signals or noise. Participants had only to choose the correct navigation direction. Therefore, the dependent variable was binary, reflecting the right or wrong choice of the direction (coded as 1 for correct navigation direction and 0 for incorrect navigation direction), and was analyzed with a generalized linear mixed-effects (GLME) model with a binomial distribution in the family. The models were accessed via the lme4 package (Bates et al., 2015) in R.

Table 6: Overview of response outcomes in Signal Detection Theory.

Stimulus type	**Participant’s response: Yes, I saw this Landmark.**	**Participant’s response: No, I did not see this Landmark.**
Signal (landmark present = target)	Hit (correct identification of the landmark)	Miss (fails to identify the landmark)
Noise (landmark absent = distractor)	False Alarm (identifies distractor as a landmark)	Correct Rejection (correct identification of the distractor)

The advantage of linear mixed-effects models is their ability to control for both fixed and random effects, which can be modified with random intercepts and random slopes, considering the variance effect between participants to achieve more precise and reliable results (Jost and Jansen, 2022). However, the best-fitting statistical model must be found first, as not every statistical model will converge due to small sample size or issues caused by overparameterization. According to (Barr et al., 2013), a recommended strategy involves starting with a complex random effect structure using only the dependent variable and no fixed effects and testing the model for convergence. If multiple models converge, the best-fitting model is selected based on the lowest Akaike information criterion (AIC) value. However, if the model fails to converge, the complexity of the random effects is reduced, and the model is retested. This process is repeated until convergence is achieved. Another important step is preparing the fixed effects for the final selected model by centering the continuous variables at the mean and contrast coding the categorical variables. Once this procedure is done, the fixed effects can be added to the selected model, and the data can be analyzed.

In the second part of the analysis, the Python script “EDA-Peak-Detection-Script” was modified to preprocess the data for statistical testing of H4 and H5. Initially, by running the code, the user is asked to provide the EDA data source and define the settings for the peak detection algorithm, which identifies skin conductance response (SCR) peaks in the data. The settings were set to the recommended default settings suggested by the script's authors (Taylor et al., 2015), including a minimum peak amplitude of 0.02, an offset of 1, a max rise time of 4 seconds, and a max decay time of 4 seconds. These settings are also described in the literature in a similar range (Dawson et al., 2007).

The script was modified to import a report file from the aTimeLogger application on the smartphone, which tracked the time windows for each part of the experiment (navigation task vs questionnaires) for every participant. This data was used to separate peaks detected during the navigation task and those detected during the questionnaires. In the next step, the average amplitude and the number of amplitudes within each respective time window were calculated and summarized. In the end, the detected peaks were visualized, and their characteristics, including peak start time, peak end time, EDA, rise time, maximum derivative, decay time, SCR width, amplitude, peak time stamp, the area under the curve (AUC) (see Figure 15), as well as the calculated average amplitude and the number of peaks for each respective time window, were saved in a .csv file and further analyzed in R.

The statistical analysis for NASA-TLX data (H3) and EDA data (H4, H5) followed the same principle. The data had to meet certain assumptions to determine the appropriate statistical test. First, the data was tested for normal distribution and homoscedasticity using the Shapiro-Wilk and Levene's tests with a significance level of p = 0.05. The average amplitude values, number of peaks, and NASA-TLX scores were used as continuous dependent variables, while the group variable served as the categorical independent variable. Since the data was unpaired because it was generated from different groups, the appropriate test was selected based on these assumptions. According to the statistical guidelines of (Nayak and Hazra, 2011), if the data was normally distributed and homoscedastic, a parametric unpaired t-test was applied. Otherwise, the non-parametric Mann-Whitney U test was used to assess statistical significance.

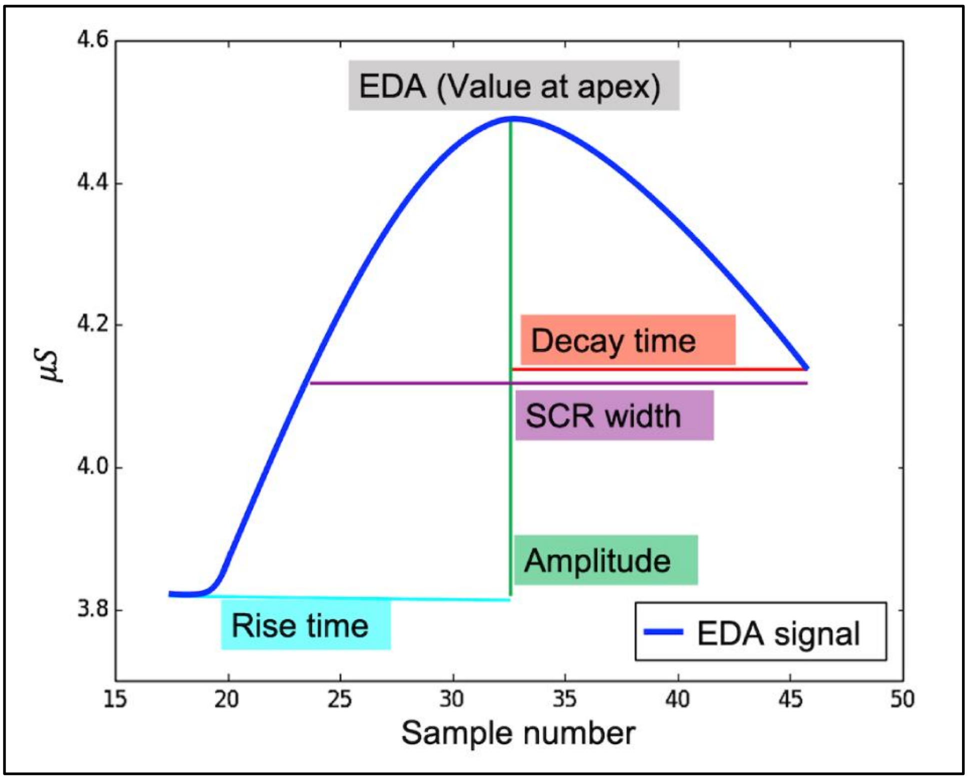


Figure 15: Overview of an electrodermal activity peak with its characteristics (Alinia et al., 2021).

4 Results

This chapter presents the results obtained from the statistical methods described in the "Data Analysis" chapter. First, a summary of the SBSOD is presented to provide an overview of the participants' spatial abilities in each group. Following this, the outcomes of the LME and GLME models related to spatial learning (H1 and H2) are reported. Lastly, the results of the NASA-TLX and the EDA data analyzed using the EDA Explorer are presented, which are related to the workload and the emotional stress (H3, H4, and H5).

4.1 Santa Barbara Sense of Direction Score Evaluation

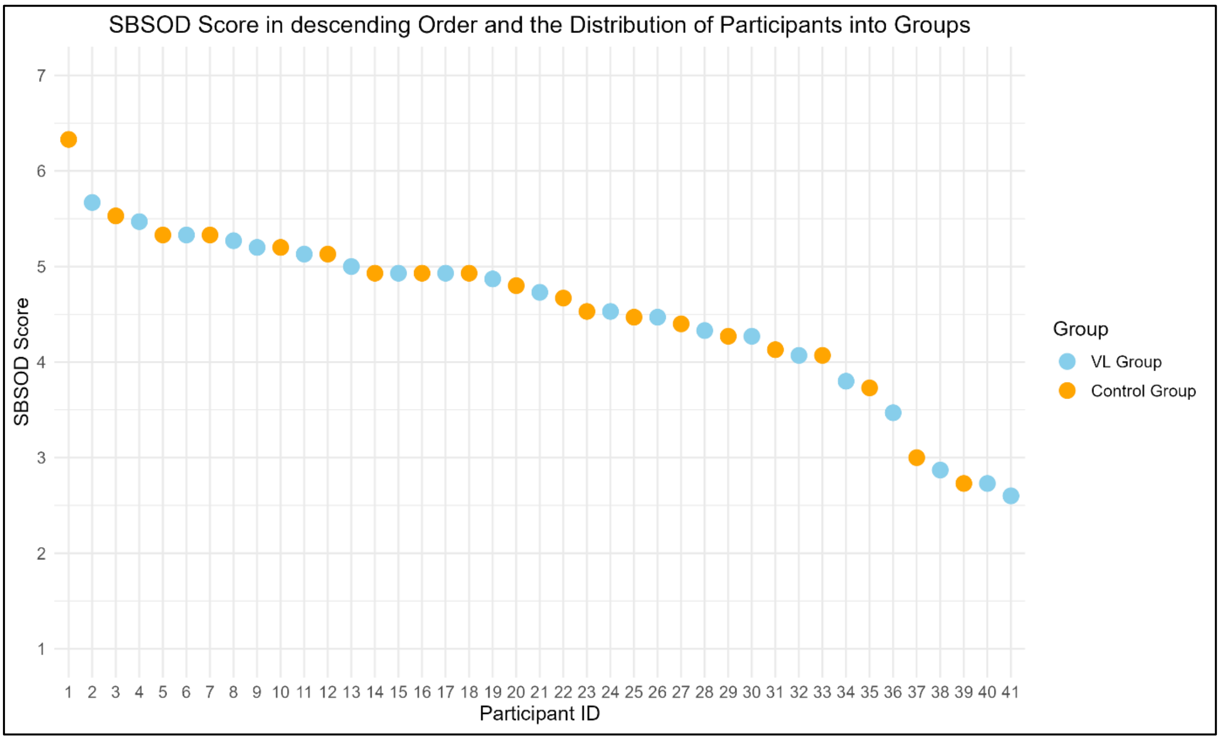


Figure 16: Visualization of SBSOD score by participant and group.

The SBSOD score ranges from 1 to 7, where 1 indicates that participants believe they have a poor sense of direction, while 7 represents that participants think they have a very good sense of direction. Figure 16 shows a summary of the SBSOD score of each participant with the corresponding group. The participants were evenly distributed between the groups, which is visible in the alternating pattern of the dots in the plot. However, a few participants did not respond during the organization process or had difficulty finding a suitable time slot and were, therefore, assigned to the groups at a later point. This disrupted the alternating allocation (see participant IDs 8, 22, and 40).

The average SBSOD score across all participants is approximately 4.54 (range 2.6-6.33), with a standard deviation of 0.87. The average SBSOD score of the VL Group is about 4.46 (range 2.6-5.67, with eleven females having an average SBSOD score of 4.16 and ten males having an average SBSOD score of 4.79), while the average SBSOD score of the Control Group is 4.62 (range 2.73-6.33, with ten females having an average SBSOD score of 4.25 and ten males average SBSOD score of 4.99). The average values (4.46 and 4.62) of the two groups indicate a balanced distribution of the participants, ensuring an equal number of participants with good and poor sense of direction in both groups.

4.2 Hypothesis 1 and Hypothesis 2

To analyze H1 and H2, the LME and GLME models were created based on the suggested algorithm described in the "Data Analysis" chapter. The final selected models included a random intercept for each participant indicated by the expression (1 | ID) in the model (see Figure 18). Four categorical fixed effects were included in the model: group (VL Group vs. Control Group), landmark type (3D objects vs. wall objects), familiarity with the route (familiar vs. not familiar), and gender (male vs. female). Additionally, one continuous variable (SBSOD score) was used in the model. The literature review by (Coluccia and Louse, 2004) suggests a gender difference in spatial orientation and spatial abilities, which should be considered. Familiarity with the study area can also influence spatial knowledge performance (Ahmadpoor et al., 2019). Furthermore, (Hegarty et al., 2002) reports a correlation between the SBSOD and acquired spatial knowledge. Therefore, it is important to control for all these effects to explain more data variance and provide more precise results. Since H1 and H2 were analyzed using the same models, their results are presented together. The effects of the model were extracted and visualized using the effects (Fox, 2003) and ggplot2 package (Wickham, 2016) in R (see Figure 17).

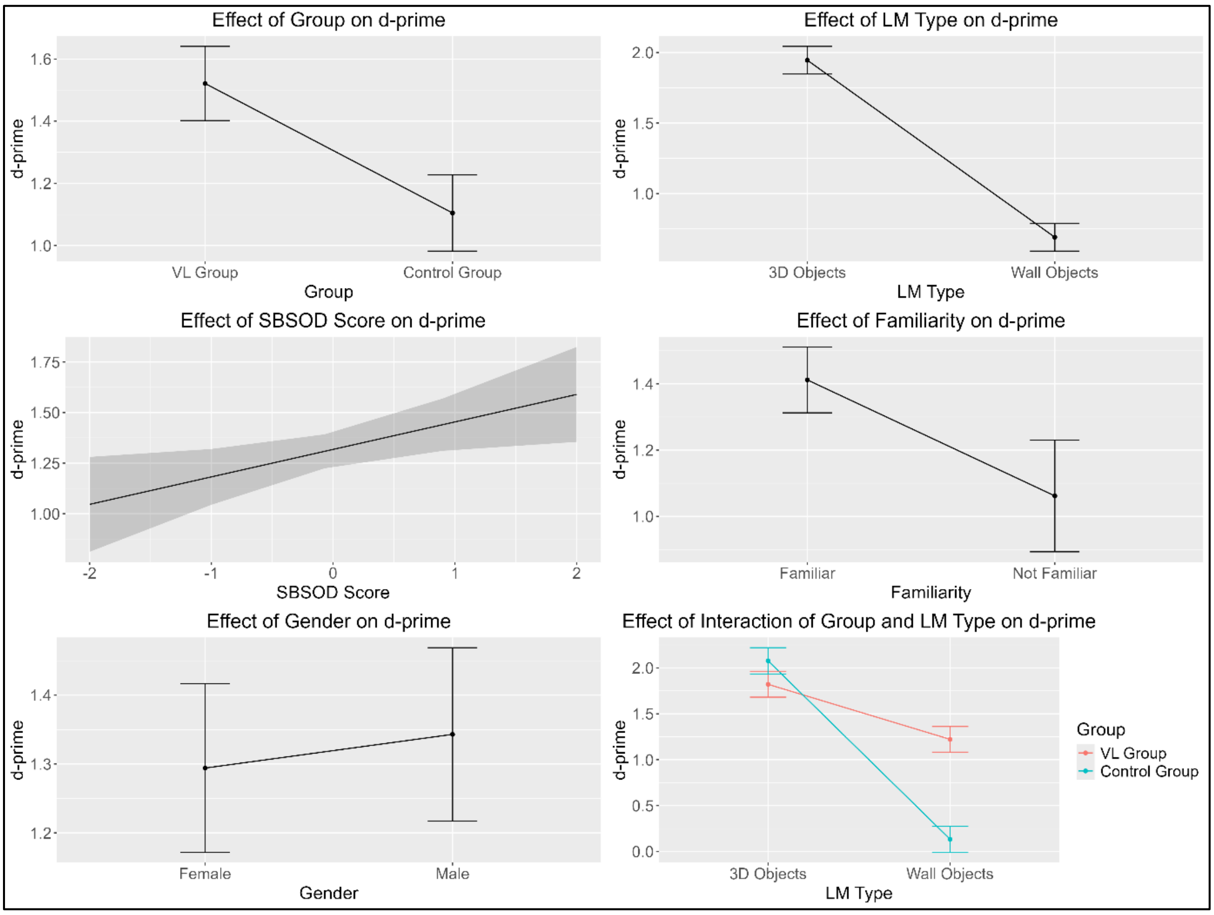


Figure 17: Visualization of effects extracted from the LME model.

```
Linear mixed model fit by REML. t-tests use Satterthwaite's method ['lmerModLmerTest']
Formula: dprime ~ Group * LM_Type + SOD_score + Familiarity_2 + Gender +      (1 | ID)
   Data: dprime_type

REML criterion at convergence: 163.8

Scaled residuals:
    Min      1Q  Median      3Q     Max
-2.3516 -0.3810 -0.1494  0.6337  2.0417

Random effects:
 Groups   Name        Variance Std.Dev.
 ID       (Intercept) 0.1755   0.4190
 Residual             0.2208   0.4699
Number of obs: 82, groups:  ID, 41

Fixed effects:
                Estimate Std. Error       df t value Pr(>|t|)
(Intercept)      1.23236    0.09603 36.00000  12.833 5.37e-15 ***
Group1           0.20820    0.08752 36.00000   2.379   0.0228 *
LM_Type1         0.63557    0.05191 39.00000  12.243 6.17e-15 ***
SOD_score        0.13592    0.10956 36.00000   1.241   0.2228
Familiarity_21   0.17508    0.10019 36.00000   1.747   0.0891 .
Gender1         -0.02447    0.09195 36.00000  -0.266   0.7917
Group1:LM_Type1 -0.33605    0.05191 39.00000  -6.473 1.14e-07 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Correlation of Fixed Effects:
            (Intr) Group1 LM_Ty1 SOD_sc Fml_21 Gendr1
Group1      -0.161
LM_Type1     0.000  0.000
SOD_score   -0.121  0.150  0.000
Familrty_21 -0.493  0.284  0.000  0.223
Gender1     -0.084  0.050  0.000  0.416  0.124
Grp1:LM_Ty1  0.000  0.000 -0.024  0.000  0.000  0.000
```

Figure 18: R output of LME model.

The output of the LME model shows that the random intercept variance (0.1755) in random effects emphasizes individual differences between the participants that cannot be fully explained by the fixed effects. Additionally, the variance in residuals (0.2208) addresses that there is still some variability within each participant in the data that is not explained by the model. To understand the entire output (see Figure 18), it is important to know the reference level for each fixed effect, which is presented in the table below. Note that SOD_score is a continuous fixed effect centered to the mean and does not have contrast coding.

Table 7: Definition of the contrast coding for the categorical fixed effects.

Fixed Effect (categorical)	Comparison value coded as 1	Reference value coded as (-1)
Group	VL Group	Control Group
LM_Type	3D objects	Wall objects
Familiarity_2	Familiar	Not Familiar
Gender	Female	Male

The results show a significant difference at the level of $p < 0.05$ for the Group effect, indicating that the VL Group has an increase of 0.2082 in d-prime value compared to the Control Group. Additionally, a significant difference at the level of $p < 0.001$ for the landmark type effect (LM_Type) is observed, highlighting an increase of 0.63557 in the d-prime value for 3D objects compared to wall objects. The last significant difference at the level of $p < 0.001$ is found in the interaction effect between group and landmark type (Group * LM_Type). This indicates that the effect of landmark type on d-prime value depends on the group. Specifically, the difference in d-prime value between wall objects (reference) and 3D objects is 0.33605 lower in the VL

Group compared to the difference observed between wall objects (reference) and 3D objects in the Control Group (reference). No significant differences are found in the effects of gender, familiarity, or SBSOD. However, the familiarity effect with a p-value of 0.0891 may suggest a trend towards statistical significance.

In the next part, the output of the GLME model responsible for testing the route knowledge is presented. Note that the contrast coding of the fixed effects remains the same as before (see Table 7). A summary of the results and visualization of the fixed effects are provided in Figure 19 and Figure 20.

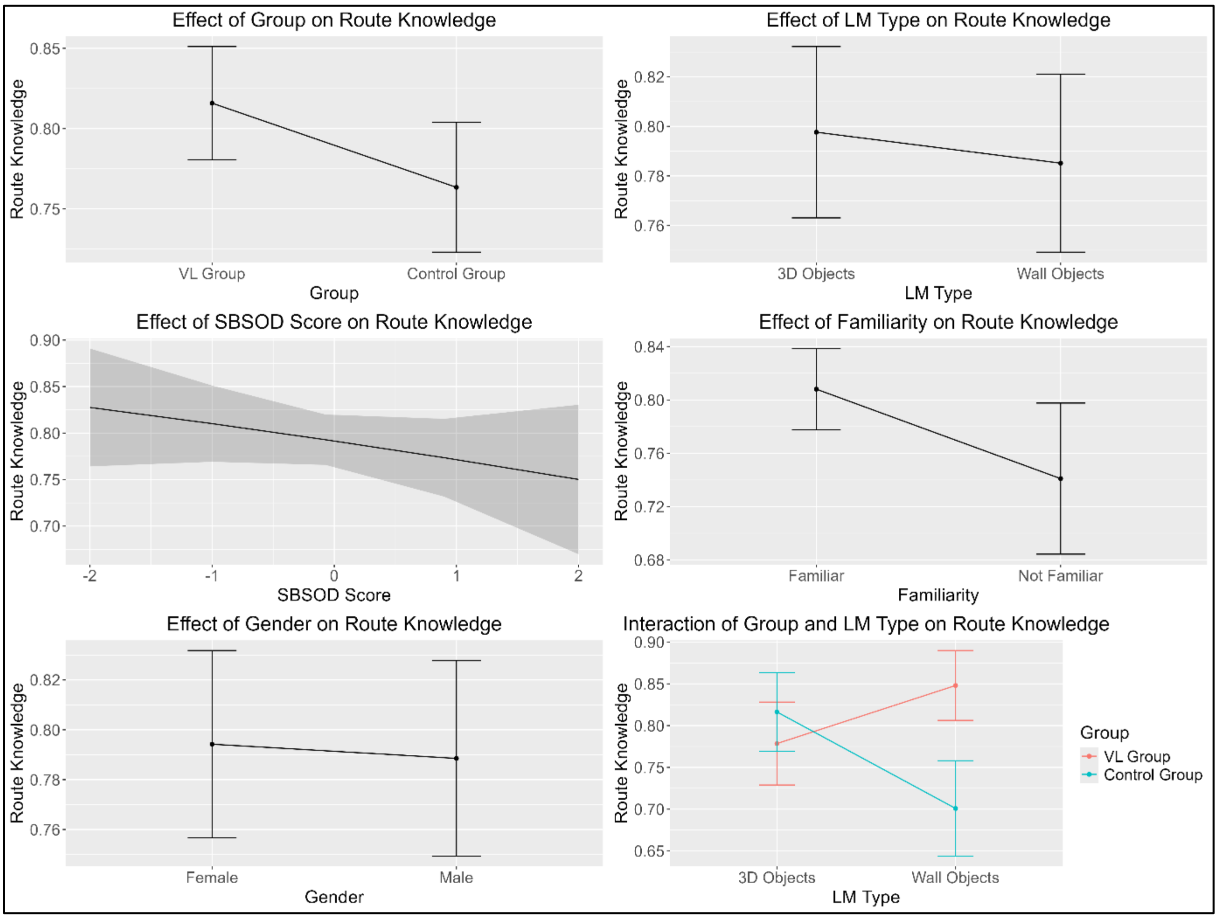


Figure 19: Visualization of effects extracted from the GLME model.

```
Generalized linear mixed model fit by maximum likelihood (Laplace Approximation) ['glmerMod']
 Family: binomial  ( logit )
Formula: Route ~ Group * LM_Type + SOD_score + Familiarity_2 + Gender +      (1 | ID)
   Data: R_df_long

     AIC      BIC   logLik deviance df.resid
   355.7    386.1   -169.9    339.7      320

Scaled residuals:
    Min      1Q  Median      3Q     Max
-2.7763  0.3602  0.4581  0.5609  0.7919

Random effects:
 Groups Name        Variance Std.Dev.
 ID     (Intercept) 0.171    0.4136
Number of obs: 328, groups:  ID, 41

Fixed effects:
                Estimate Std. Error z value Pr(>|z|)
(Intercept)      1.24001    0.17714   7.000 2.55e-12 ***
Group1           0.15843    0.16115   0.983   0.3255
LM_Type1         0.04458    0.13744   0.324   0.7457
SOD_score       -0.11725    0.20225  -0.580   0.5621
Familiarity_21   0.19318    0.17819   1.084   0.2783
Gender1          0.01725    0.16540   0.104   0.9169
Group1:LM_Type1 -0.27591    0.13776  -2.003   0.0452 *
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Correlation of Fixed Effects:
            (Intr) Group1 LM_Ty1 SOD_sc Fml_21 Gendr1
Group1      -0.105
LM_Type1     0.013 -0.121
SOD_score   -0.158  0.140 -0.003
Familrty_21 -0.395  0.317 -0.004  0.213
Gender1     -0.088  0.064 -0.003  0.404  0.139
Grp1:LM_Ty1 -0.125  0.001  0.033  0.009 -0.016  0.000
```

Figure 20: R output of GLME model.

The variance value of 0.171 in random intercepts for the ID reveals some variation in the intercepts across different participants that cannot be fully explained by the fixed effects. Additionally, a significant difference in the interaction effect between group and landmark type (Group * LM_Type) is found for a level of $p < 0.05$. This shows that the effect of landmark type (LM_Type) on the binary route variable, which reflects the hit or miss of the participants' choice of direction, depends on the group. In other words, the difference in the route variable between wall objects (reference) and 3D objects is 0.27591 lower in the VL Group compared to the difference observed between wall objects (reference) and 3D objects in the Control Group (reference). For all other fixed effects, including group, landmark type, SBSOD, familiarity, and gender, no significant differences are found.

4.3 Hypothesis 3

The boxplots of the NASA-TLX score for the VL Group and the Control Group (see Figure 21) show a relatively small workload in both groups with a small trend where the VL Group has a higher mean of the NASA-TLX score compared to the Control Group, suggesting that there might be a significant difference. To assess this difference, the data was first tested for normal distribution and homoscedasticity using the Shapiro-Wilk and Levene's tests, with a significance level of p = 0.05, to determine the appropriate statistical test.

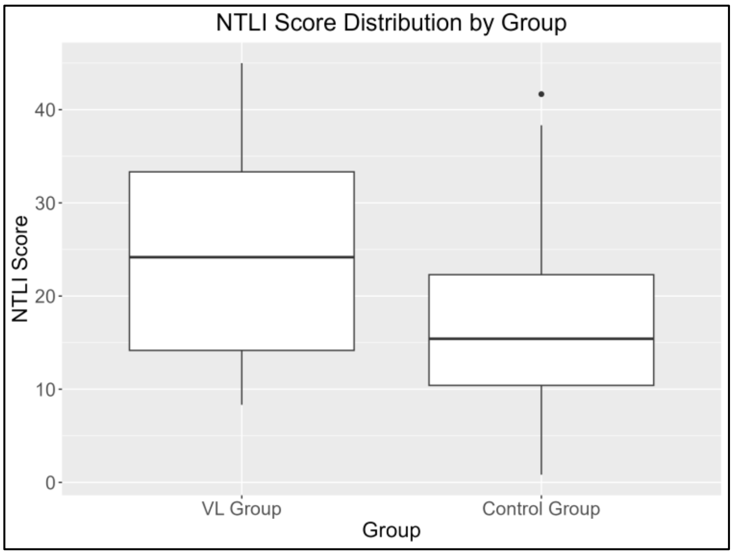


Figure 21: Boxplots of NASA-TLX scores for VL Group and Control Group.

```
        Shapiro-Wilk normality test

data:  Emotions_df$NTLI_score
W = 0.956, p-value = 0.1138
```

```
Levene's Test for Homogeneity of Variance (center = median)
      Df F value Pr(>F)
group  1  0.2862 0.5957
      39
```

Figure 22: Shapiro-Wilk and Levene's test results for the NASA-TLX scores.

The Shapiro-Wilk and Levene's test results reveal that the NASA-TLX scores are normally distributed (W = 0.956, p = 0.1138) and that homoscedasticity is given between the two groups (p = 0.5957) (see Figure 22). Therefore, the unpaired parametric t-test is the appropriate statistical test for this analysis.

```
        Two Sample t-test

data:  NTLI_score by Group
t = 1.7651, df = 39, p-value = 0.08537
alternative hypothesis: true difference in means between group VL Group and group Control Group is not equal to 0
95 percent confidence interval:
 -0.9179096 13.4993858
sample estimates:
     mean in group VL Group mean in group Control Group
               24.16524                 17.87450
```

Figure 23: Results of the unpaired t-test comparing NASA-TLX scores means between the VL Group and the Control Group.

The result of the unpaired parametric t-test (p = 0.08537) (see Figure 23) shows no significant difference in the mean of the NASA-TLX scores between the VL Group and the Control Group. However, since the p-value is close to the significance threshold of 0.05, it indicates a tendency towards significance.

4.4 Hypothesis 4

Figure 24 shows an example of the output from the modified “EDA-Peak-Detection-Script”, which was used to identify and summarize the skin conductance response (SCR) peaks of the EDA data collected with the Empatica E4 wristband for each participant. The red window represents the navigation time window, while the grey windows represent the post-navigational questionnaire time windows of the experiment. The EDA signal is highlighted with the blue line, and the peaks are visualized as green vertical lines. The peaks were summarized for both time conditions (navigation task vs. post-navigational questionnaires) and saved in a .csv file (see Figure 25).

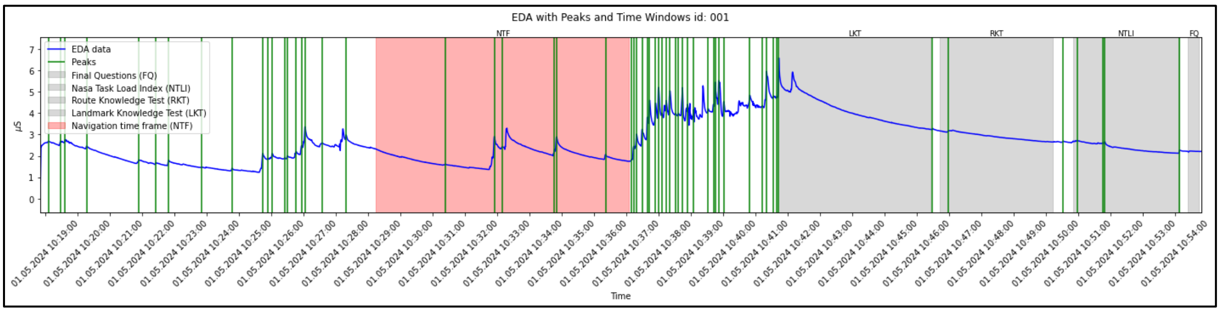


Figure 24: EDA Explorer output for subject 001.

```
Von,Bis,Typ,Dauer,peaks_in_window,EDA,rise_time,max_deriv,decay_time,SCR_width,amp,peak_time_stamp,AUC
01.05.2024 10:54:24,01.05.2024 10:54:45,Final Questions (FQ),00:00:21,0,,,,,,,,
01.05.2024 10:50:50,01.05.2024 10:54:08,Nasa Task Load Index (NTLI),00:03:18,3,2.717605,1.75,0.03670938762210341,1.875,3.25,0.02691299999999952,01.05.2024 10:19:06,0.08746724999999844
01.05.2024 10:50:50,01.05.2024 10:54:08,Nasa Task Load Index (NTLI),00:03:18,3,2.602264,2.5,0.022875907365790482,1.25,2.75,0.027553499999999786,01.05.2024 10:19:28,0.07577212499999941
01.05.2024 10:50:50,01.05.2024 10:54:08,Nasa Task Load Index (NTLI),00:03:18,3,2.6394295,1.875,0.08054344977131933,0.25,2.0,0.044213499999999684,01.05.2024 10:19:36,0.08842699999999937
01.05.2024 10:46:43,01.05.2024 10:50:13,Route Knowledge Test (RKT),00:03:30,1,3.182429,2.875,0.033901519559318416,,,0.0563889999999998,01.05.2024 10:20:16,
01.05.2024 10:41:43,01.05.2024 10:46:26,Landmark Knowledge Test (LKT),00:04:43,1,6.30643,2.375,1.9332758534430923,2.125,3.5,1.5380949999999993,01.05.2024 10:21:53,5.383332499999998
01.05.2024 10:29:15,01.05.2024 10:37:05,Navigation time frame (NTF),00:07:50,6,1.603869,1.375,0.04549268474505119,1.75,2.875,0.022426999999999975,01.05.2024 10:22:25,0.06447762499999993
01.05.2024 10:29:15,01.05.2024 10:37:05,Navigation time frame (NTF),00:07:50,6,2.884009,2.625,0.5209005492696122,,,0.9469339999999997,01.05.2024 10:22:49,
01.05.2024 10:29:15,01.05.2024 10:37:05,Navigation time frame (NTF),00:07:50,6,2.415598,3.125,0.016557710709555806,2.625,5.375,0.06920450000000011,01.05.2024 10:23:51,0.3719741875000006
01.05.2024 10:29:15,01.05.2024 10:37:05,Navigation time frame (NTF),00:07:50,6,2.2611695000000003,1.5,0.22071784676566963,,,0.08202000000000043,01.05.2024 10:24:47,
01.05.2024 10:29:15,01.05.2024 10:37:05,Navigation time frame (NTF),00:07:50,6,2.859019,2.625,0.49802500651844994,3.75,5.5,0.6221990000000002,01.05.2024 10:25:44,3.422094500000001
01.05.2024 10:29:15,01.05.2024 10:37:05,Navigation time frame (NTF),00:07:50,6,2.049853,2.75,0.12863286468720325,,,0.21017600000000014,01.05.2024 10:25:54,

Metric,Value,Count
Average of Navigation Amplitudes,0.32549341666666676,6
Average of Test Amplitudes,0.3386327999999996,5
```

Figure 25: Summary of peaks information for subject 001.

The .csv file consists of each peak detected during one of the time windows with its corresponding characteristics, including peak start time, peak end time, number of peaks in the window, EDA, rise time, maximum derivative, decay time, SCR width, amplitude, peak time stamp, AUC, as well as the number of peaks and the average amplitudes among the corresponding time windows (see Figure 25).

To assess the differences between the groups in the number of SCR peaks and the average amplitudes during navigation, the data was summarized and tested for normal distribution and homoscedasticity using the Shapiro-Wilk and Levene’s tests, with a significance level of p = 0.05. However, the visualization of the data (see Figure 26) already suggests that there might be no significant differences because the means are very close and no clear trend is visible.

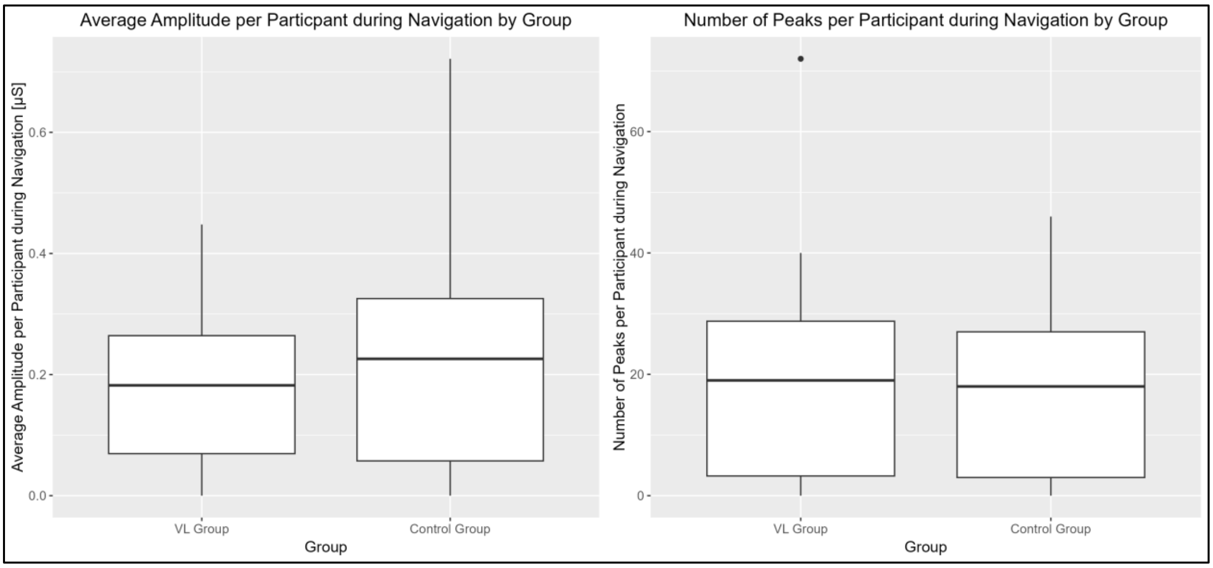


Figure 26: Boxplots of average amplitude (left) and number of peaks (right) per participant during navigation by group.

First, the average amplitudes during navigation between the VL Group and the Control Group are analyzed, followed by an analysis of the number of SCR peaks during navigation between the two groups.

```
        Shapiro-Wilk normality test

data:  EDA_df$Average_nav_amplitudes
W = 0.92254, p-value = 0.01689
```

```
Levene's Test for Homogeneity of Variance (center = median)
      Df F value Pr(>F)
group  1   1.031 0.3173
      33
```

Figure 27: Shapiro-Wilk and Levene's test results for average amplitudes during navigation.

The results of the Shapiro-Wilk and Levene's test indicate that the average navigation amplitudes are not normally distributed (W = 0.92254, p = 0.01689), but the variance between the groups is homogeneous (p = 0.3173) (see Figure 27). Based on these results, the unpaired non-parametric Mann-Whitney U test was applied.

```
        Wilcoxon rank sum test with continuity correction

data:  Average_nav_amplitudes by Group
W = 124, p-value = 0.345
alternative hypothesis: true location shift is not equal to 0
```

Figure 28: Mann-Whitney U test results comparing the average navigation amplitudes between the VL Group and the Control Group.

The outcome of the Mann-Whitney U test (W = 124, p = 0.345) (see Figure 28) shows no significant difference in the average amplitudes during navigation between the VL Group and the Control Group.

Next, the number of SCR peaks during navigation between the two groups was analyzed.

```
        Shapiro-Wilk normality test

data:  EDA_df$Nav_peaks
W = 0.89632, p-value = 0.003154
```

```
Levene's Test for Homogeneity of Variance (center = median)
      Df F value Pr(>F)
group  1  0.0574 0.8121
      33
```

Figure 29: Shapiro-Wilk and Levene's test results for the number of peaks during navigation.

The results of the Shapiro-Wilk and Levene's test show that the number of peaks during navigation is not normally distributed (W = 0.89632, p = 0.003154), but the variance is homogeneous between the groups (p = 0.8121) (see Figure 29). Thus, the unpaired non-parametric Mann-Whitney U test was applied.

```
        Wilcoxon rank sum test with continuity correction

data:  Nav_peaks by Group
W = 158.5, p-value = 0.8683
alternative hypothesis: true location shift is not equal to 0
```

Figure 30: Mann-Whitney U test results comparing the number of peaks during navigation between the VL Group and the Control Group.

The result of the Mann-Whitney U test (W = 158, p = 0.8683) (see Figure 30) shows no significant difference in the number of SCR peaks during navigation between the VL Group and the Control Group.

4.5 Hypothesis 5

The same procedure was used to evaluate whether there is a significant difference between the VL Group and Control Group in the number of SCR peaks and average amplitudes during the post-navigational questionnaires phase. Figure 31 illustrates that the means of the average amplitude per participant during the questionnaires are very close, indicating that there is no statistical difference. In contrast, there is a small difference visible in the number of peaks per participant, which may suggest a trend towards statistical difference. The data were tested for normal distribution and homoscedasticity using the Shapiro-Wilk and Levene's tests, with a significance level of p = 0.05.

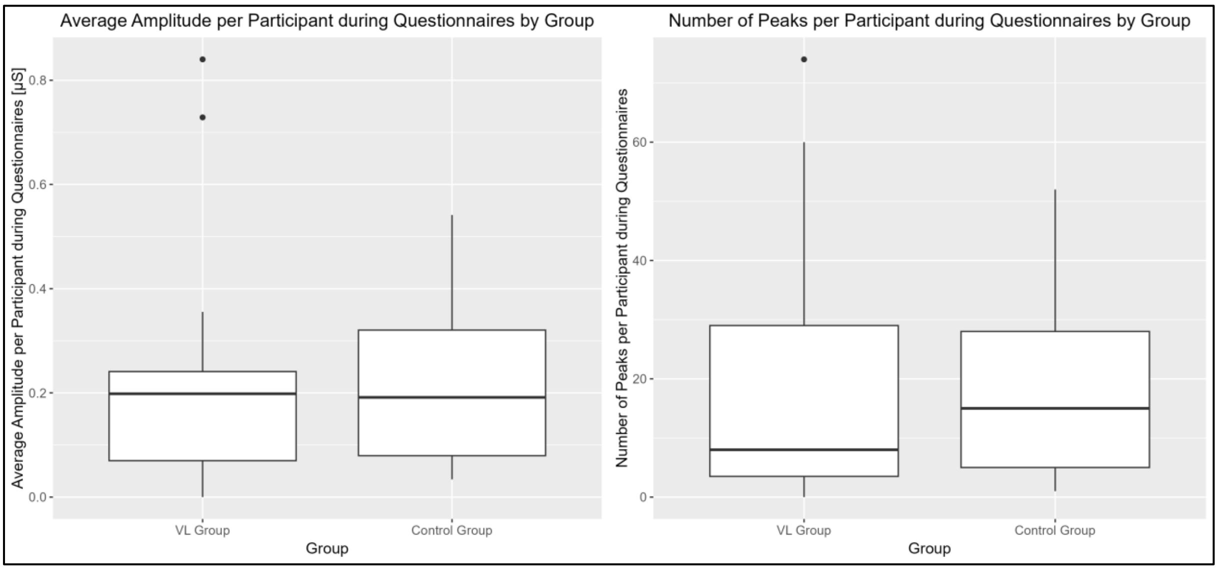


Figure 31: Boxplots of average amplitude (left) and number of peaks (right) per participant during the questionnaires by group.

```
        Shapiro-Wilk normality test

data:  EDA_df$Average_test_amplitude
W = 0.8676, p-value = 0.0005939
```

```
Levene's Test for Homogeneity of Variance (center = median)
      Df F value Pr(>F)
group  1  0.1658 0.6865
      33
```

Figure 32: Shapiro-Wilk and Levene's test results for average amplitude during the questionnaires.

The results of the Shapiro-Wilk and Levene's test show that the average amplitudes during the questionnaires phase are not normally distributed (W = 0.8676, p = 0.0005939) and that the variance between the groups is homogeneous (p = 0.6865) (see Figure 32). As a result, the unpaired non-parametric Mann-Whitney U test was used to assess statistical significance.

```
        Wilcoxon rank sum test with continuity correction

data:  Average_test_amplitudes by Group
W = 140, p-value = 0.6799
alternative hypothesis: true location shift is not equal to 0
```

Figure 33: Mann-Whitney U test results comparing the average amplitudes during the post-navigational questionnaires between the VL Group and the Control Group.

The outcome of the Mann-Whitney U test (W = 140, p = 0.6799) (see Figure 33) shows no significant difference in the average amplitudes during the post-navigational questionnaires phase between the VL Group and the Control Group.

Next, the number of SCR peaks during the post-navigational questionnaires phase between the two groups was analyzed.

```
        Shapiro-Wilk normality test

data:  EDA_df$Test_peaks
W = 0.83516, p-value = 0.0001081
```

```
Levene's Test for Homogeneity of Variance (center = median)
      Df F value Pr(>F)
group  1  0.3193 0.5758
      33
```

Figure 34: Shapiro-Wilk and Levene's test results for the number of peaks during the post-navigational questionnaires.

The results of the Shapiro-Wilk and Levene's test show that the number of peaks during the post-navigational questionnaires phase is not normally distributed (W = 0.83516, p = 0.0001081), but the homoscedasticity is given between the groups (p = 0.5758) (see Figure 34). Therefore, the unpaired non-parametric Mann-Whitney U test was used to assess statistical significance.

```
        Wilcoxon rank sum test with continuity correction

data:  Test_peaks by Group
W = 137, p-value = 0.6085
alternative hypothesis: true location shift is not equal to 0
```

Figure 35: Mann-Whitney U test results comparing the number of peaks during the post-navigational questionnaires between the VL Group and the Control Group.

The result of the Mann-Whitney U test (W = 137, p = 0.6085) (see Figure 35) shows no significant difference in the number of SCR peaks during the post-navigational questionnaires phase between the VL Group and the Control Group.

5 Discussion

5.1 Enhancing Environmental Awareness and Spatial Learning with Virtual Landmarks during Indoor Navigation in MR

***Research Question 1**: Do virtual landmarks increase the awareness of the physical environment and enhance spatial learning during indoor navigation in MR?*

***Hypothesis 1:** Integrating virtual landmarks as symbolic recreation in front of the physical landmarks for the MR indoor navigation environment enhances spatial learning compared to navigation with only physical landmarks.*

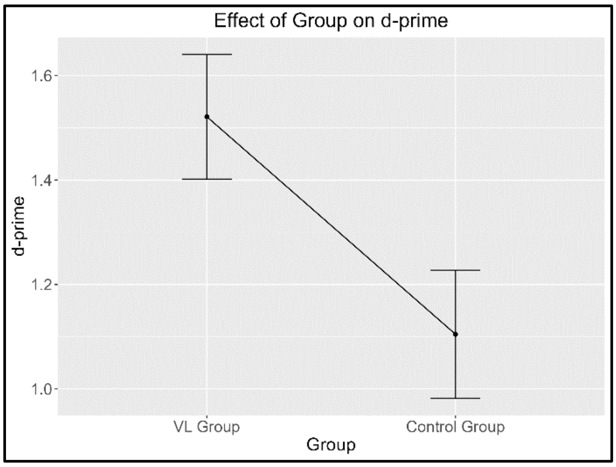


Figure 36: Visualization of the significant group effect in the LME model.

The findings support Hypothesis 1 regarding landmark knowledge, showing a significant increase in the d-prime value for the virtual landmark group (see Figures 18 and 36). This suggests that participants exposed to the virtual landmarks can better differentiate between real landmarks encountered during navigation and those not visible on the route. These results are also supported by the research of (Liu et al., 2021) which reports that spatial knowledge acquisition is possible using virtual semantic landmarks during indoor navigation in a MR environment. In contrast, the study of (Zhao et al., 2023) suggest that highlighting the landmarks does not increase spatial knowledge acquisition when navigating with holographic aids in a fixed world frame environment. However, their study was performed in a VR environment with augmented elements and should be interpreted cautiously when applied in a MR environment, as it could lead to different results due to different environments.

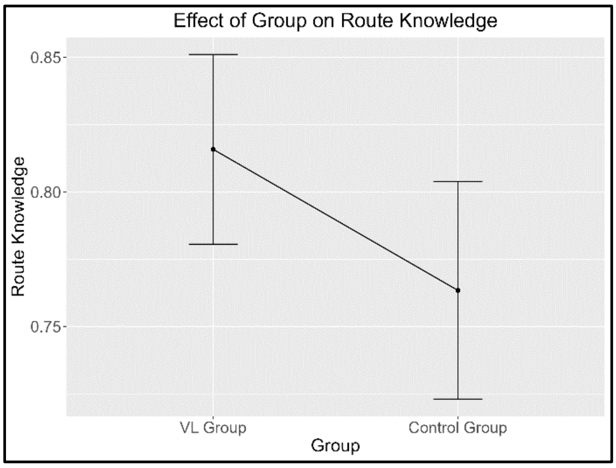


Figure 37: Visualization of the non-significant group effect in the GLME model.

At the same time, the thesis findings do not support Hypothesis 1 regarding route knowledge because no significant difference was found between the two groups. Nonetheless, the results and the visualization of the extracted effects (see Figures 20 and 37) show that both groups performed well, with the VL Group having a small advantage over the Control Group. According to (Siegel and White, 1975), landmark knowledge is acquired first, followed by route knowledge. On the one hand, it is possible to argue that although there is a significant difference in the landmark knowledge performance between the two groups, it was sufficient for both groups to build good route knowledge. On the other hand, the small advantage of the VL Group might suggest that the experiment was not long or complex enough to identify significant differences in route knowledge. For this reason, the difficulty of the route knowledge test should be adapted in future research, including other methods for route knowledge testing, e.g., route sketching as performed by (Rehman and Cao, 2017) or route retracing, where the participants must navigate back to the starting point from the destination (Wiener et al., 2012). These tests might provide more valuable data to identify significant differences. However, such tests could not be conducted in this study because of the one-hour time limit per session.

Hypothesis 2: *There is a significant difference in the effect of landmark type on spatial knowledge acquisition depending on whether virtual landmarks are displayed in front of physical landmarks.*

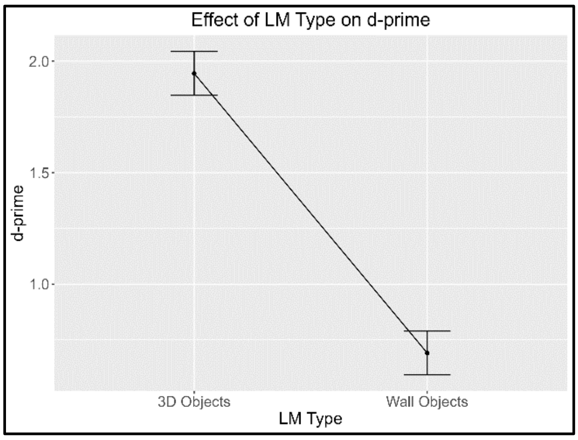


Figure 38: Visualization of the significant landmark type effect in the LME model.

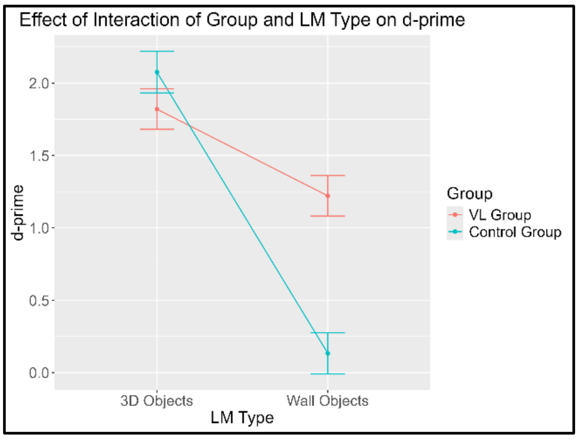


Figure 39: Visualization of the significant interaction effect of the LME model.

To address Hypothesis 2, it is important to consider the fixed effects of landmark type, group, and their interaction to understand the overall picture. As discussed in H1, there is a significant difference in the group effect for landmark knowledge (see Figures 18 and 36). Additionally, there is a significant difference for the landmark type effect (see Figures 18 and 38), indicating that distinguishing between real and fake 3D objects is easier than between real and fake wall objects. In general, it also implies that 3D objects are recognized much better than wall objects. This might be explained by the surrounding area, which defines what is considered a landmark (Millonig and Schechtner, 2007). Wall objects are flat and merge more with the indoor surroundings, e.g., walls, especially when they are small and not highlighted with bright colors, which makes them easier to overlook than the outstanding 3D objects. The interaction effect of group and landmark type also shows a significant difference in d-prime value, supporting the second hypothesis regarding landmark knowledge and demonstrating that the impact of landmark type on d-prime value depends on the group. In other words, the interaction effect of landmark type and group reveals that the VL Group has a significantly smaller increase in d-prime value when comparing 3D objects to wall objects, compared to the Control Group (see Figures 18 and 39). This suggests that virtual landmarks helped remember wall objects almost as well as 3D objects (indicated by a small difference). In contrast, the Control Group had more difficulty remembering wall objects than 3D objects (indicated by a larger difference). A possible explanation for that could be that by augmenting the wall objects with virtual landmarks, they become more outstanding to the observer and increase spatial knowledge acquisition. On the other hand, the 3D objects seem to be recognized very well due to their outstanding presence in the environment and do not require further augmentation. The visualization of the interaction effect (see Figure 39) hints at these patterns, indicating the potentially significant difference between the VL Group and the Control Group for wall objects. This suggests that the virtual landmarks might have had a significant effect on spatial knowledge acquisition for the wall objects. However, to answer this question, a further post-hoc analysis is required.

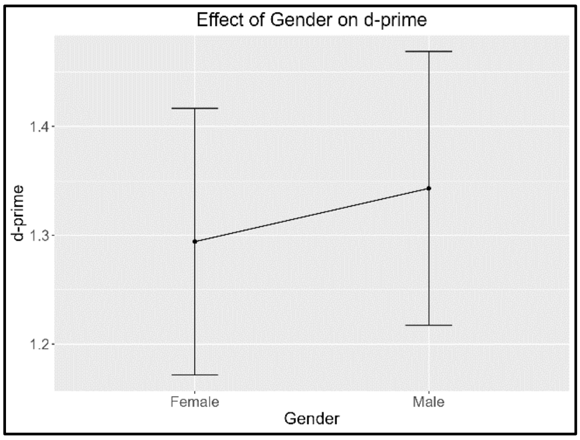


Figure 40: Visualization of the non-significant gender effect of the LME model.

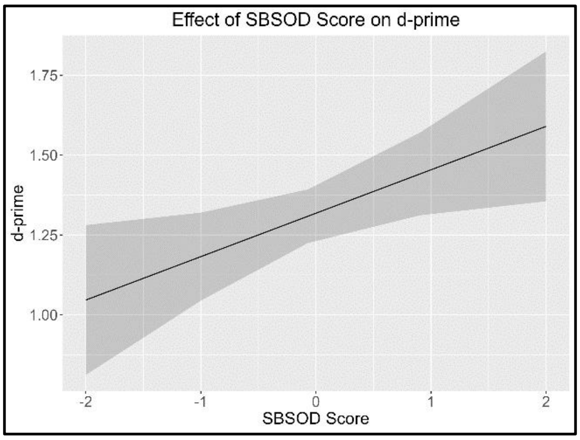


Figure 41: Visualization of the non-significant SBSOD score effect of the LME model.

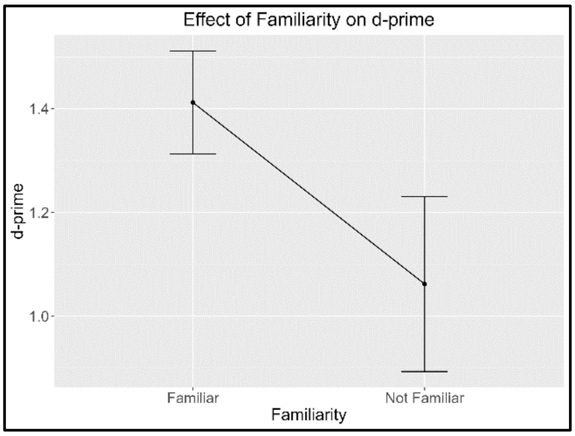


Figure 42: Visualization of non-significant familiarity effect of LME model.

Besides answering the hypothesis, the impact of other fixed effects was also analyzed. The fixed effects, including gender, familiarity with the study area, and the SBSOD, show no significant differences (see Figures 18, 40, 41, and 42). It is surprising to see that the familiarity effect does not show a significant difference but only a trend, suggesting that participants familiar with the route have a higher d-prime value. As reported by (Ahmadpoor et al., 2019), the familiarity effect is very important and can influence spatial knowledge acquisition. The reason for the lack of significance could be due to the low number of participants who were unfamiliar with the route. The familiarity effect was collected using a five-level Likert scale (1 = very unfamiliar to 5 = very familiar) in the Final Questionnaire. For the analysis, the responses were summarized into two statements: familiar (including levels 2 to 5) and not familiar (including level 1), which resulted in only 11 participants that were not familiar with the route, compared to the vast majority (30 participants) who were at least somehow familiar with the route. Subsequently, this effect must be interpreted with caution. Additionally, the results suggest that men perform slightly better than women, but this effect is marginal. The literature points out that in most cases, men should outperform women in wayfinding tasks, especially when spatial knowledge is acquired for the first time through direct interaction with the environment, but this is not always the case (Coluccia and Louse, 2004). Lastly, the lack of significant differences regarding the SBSOD is also surprising because many studies report a correlation between the SBSOD score and acquired spatial knowledge (Hegarty et al., 2002). A possible explanation could be that participants might over- or underestimate their sense of direction or because the Landmark Knowledge Test used in this study does not require the specific types of skills captured by the SBSOD.

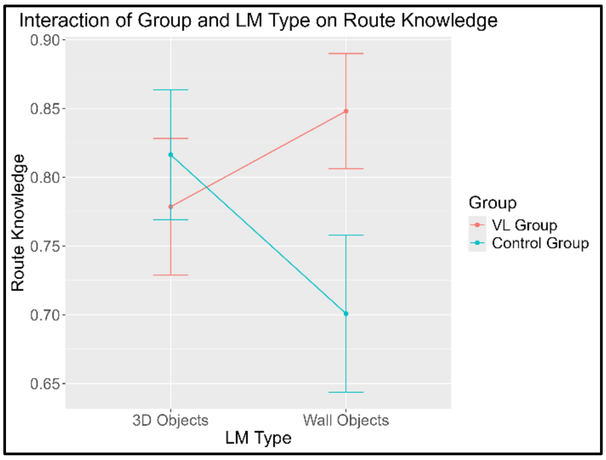


Figure 43: Visualization of the significant interaction effect of the GLME model.

The second hypothesis related to route knowledge is also supported due to the significant difference in the interaction effect of landmark type and group of the GLME model, suggesting that remembering the right turn at each intersection where the corresponding landmark type (3D object vs. wall objects) is located depends on whether the participants navigated with virtual landmarks or without them (see Figures 20 and 43). The results show a similar pattern to the landmark knowledge test, indicating that the difference between wall objects and 3D objects in choosing the right turn is smaller in the VL Group compared to the Control Group (see Figures 20 and 43). This may suggest that augmenting wall objects helps to remember the right direction at the intersection, while the 3D objects are already outstanding and show no improvement when augmented with virtual landmarks. However, this is only a visible pattern that requires a post-hoc analysis and further studies for confirmation. Compared to the results of the LME, this is the only significant effect, which means that virtual landmarks do not improve the route knowledge as discussed in H1, and the landmark type alone at each intersection does not affect remembering the right turn at the intersection. It shows a small improvement for the 3D objects, but this effect is marginal. This is surprising, but it can be explained in the same way as before that the experiment was not long or complex enough to identify significant differences in route knowledge and may require different approaches in future research.

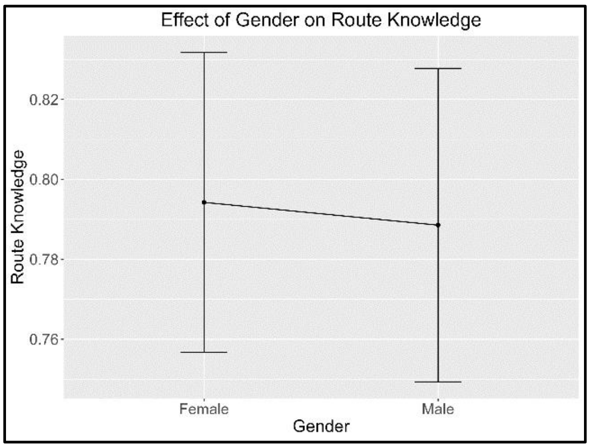


Figure 45: Visualization of the non-significant gender effect of the GLME model.

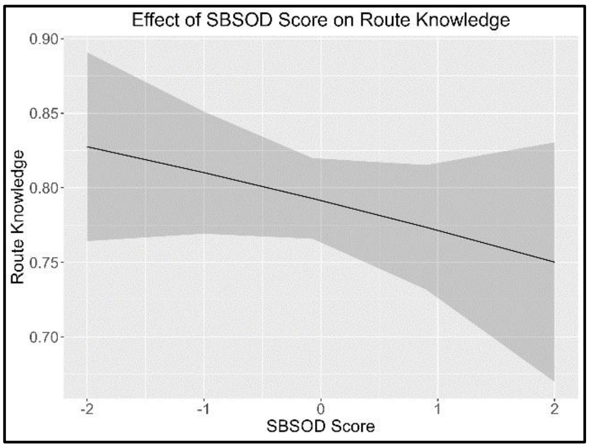


Figure 44: Visualization of the non-significant SBSOD score effect of the GLME model.

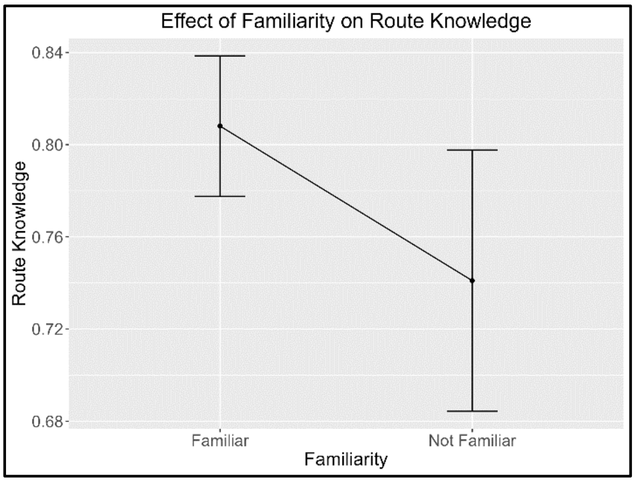


Figure 46: Visualization of the non-significant familiarity effect of the GLME model.

The other fixed effects related to gender, familiarity, and the SBSOD (see Figures 44, 45, and 46) can also be argued in the same way as previously discussed. Gender effects can differ in some cases. In this case, females showed a slightly better performance compared to the Landmark Knowledge Test, where the males performed slightly better than females. The familiarity effect can be caused by the low number of participants who were not familiar with the route, and SBSOD results can be caused by participant over- and underestimation or because the Route Knowledge Test does not require the specific types of orientation skills captured by the SBSOD. The results might also be influenced because the test was not long and complex enough. Surprisingly, the SBSOD score even shows a negative relation to the Route Knowledge Test, highlighting one more time that other, more precise approaches should be considered for route knowledge testing.

To sum it up, there is good evidence that virtual landmarks increase the awareness of the physical environment and enhance spatial learning during the indoor navigation in the MR environment. However, further research is required to analyze specific questions about how strong this effect is regarding the landmark types and route knowledge.

5.2 Impact of Visualization Design on Workload and Emotional Stress When Solving the Post-Navigational Questionnaires

Research Question 2*: How does this design affect the workload while navigating in the MR environment and the emotional stress when solving the post-navigational questionnaires?*

Hypothesis 3*: The virtual landmark group has a significantly higher workload, indicated by the NASA-TLX than the group navigated without them.*

Hypothesis 4*: There is a significant difference in the average amplitude and the number of identified skin conductance response peaks during navigation between the group navigated with virtual landmarks and the group navigated without them.*

Hypothesis 3 and Hypothesis 4 are discussed together since they are related to the workload while navigating within the MR environment. The results show no significant difference in the NASA-TLX scores between the two groups, addressing that the virtual landmarks do not increase the workload during navigation, resulting in rejecting Hypothesis 3. Although the results are not significant, a trend is visible, and more research is required to understand how the virtual landmarks are related to the workload during navigation, which is also supported by the literature because AR can have different effects on workload during a specific task (Deshpande and Kim, 2018; Yang et al., 2019).

The physiological reaction data obtained with the EDA sensor from the Empatica E4 wristband, which provided an indirect measurement of cognitive load during the navigation task in the MR environment, shows no significant difference in either the average amplitude peaks of the EDA signals or the number of peaks between the two groups, suggesting no increase in emotional arousal during navigation with virtual landmarks. Therefore, Hypothesis 4 can be rejected. This is not surprising as the EDA signals can be influenced by various factors, such as technical issues (e.g., loose electrode), movement (especially by intensified tasks e.g., navigating upstairs), environmental temperature, stress or emotional stimuli (e.g., people staring at the participant wearing the HoloLens, loud noise, etc.) (Boucsein, 2012; Gashi et al., 2020). Although a low-pass filter with the EDA-Peak-Detection-Script provided by (Taylor et al., 2015) was applied to reduce and smoothen the artifacts, it was unable to remove the large-magnitude artifacts, which might explain these results.

In conclusion, no cognitive load effects caused by the virtual landmarks were detected in the EDA data. This could be because the effect was too weak and was lost due to large artifacts or because virtual landmarks did not cause any effects at all. By applying more advanced filters and algorithms in future research to remove all artifacts in the data, more evidence can be gained, to draw better conclusions.

***Hypothesis 5**: There is a significant difference in the average amplitude and the number of identified skin conductance response peaks when solving the post-navigational questionnaires between the group navigated with virtual landmarks and the group navigated without them.*

The results show no significant difference in either the average amplitude peaks of the EDA signals or the number of peaks between the two groups during the post-navigation questionnaires phase, indicating that the visualization design does not affect the stress level when solving the post-navigational questionnaires (Landmark Knowledge Test, Route Knowledge Test, NASA-TLX test, Final Questionnaire). This suggests that using the virtual landmarks during navigation in the MR environment did not lead to greater confidence or lower stress levels compared to the Control Group during the post-navigational questionnaires phase.

In summary, no evidence was found that virtual landmarks influence the workload during navigation in the MR environment. However, the NASA-TLX suggests a slight trend without a statistical difference, indicating that further research should be elaborated. Lastly, the visualization design shows no effects on emotional stress during the post-navigational questionnaires phase.

5.3 Limitations

The Microsoft HoloLens 2 has a lot of technical and environmental limitations related to mapping, positioning, and correct visualization of the holograms in the environment. During the study, various problems arose while using the Microsoft HoloLens 2. The main problem is that the hologram position is saved based on the spatial map created by the HoloLens when encountering a new environment for the first time. Walking and scanning the environment multiple times enhances the spatial map with more details, including wall structures and objects featured in that environment. However, this approach can be inaccurate and unreliable for navigation use cases due to several technical and environmental aspects.

First, the HoloLens is very sensitive to light and reflection conditions, leading to an imprecise hologram position (see Figure 47) or, even worse, to a loss of the entire environment. As a result, the HoloLens will try to recalibrate the environment. At this point, two scenarios can happen. In the first scenario, the HoloLens finds the same environment and visualizes the holograms in a precise position (see Figure 50). In the second scenario, on the other hand, the HoloLens redirects the position to a similar place in the environment, an issue called wormhole (Lolambean, 2022), resulting in the visualization of wrong holograms. During the experiment, this happened to two participants who transitioned from floor G to floor H on the red-black stairs Y38 (landmark 12) because both floors looked almost identical. When navigating upstairs from floor G, the HoloLens lost the environment, recalibrated on floor H, and tricked itself by thinking it was located on floor G, causing the visualization of all holograms from floor G on floor H (see Figures 48, 49, and 50). This led to an interruption of the experiment session, followed by an additional check before the next session to ensure that the holographic arrows were in the right place and would not misguide the participants.

The HoloLens can lose the environment for various reasons, including different light and reflection conditions, but also due to fast movement, head shaking during navigation, or environmental changes such as public events or newly added or shifted objects (e.g., tables, opened doors, cleaning carts). Even a group of people standing in front of an important object can sometimes cause issues. Additionally, the holographic device has an additive display (Mavitazk, 2022), resulting in white appearing bright and black appearing transparent. Since dark objects do not reflect light very well, the device has difficulties measuring the depth of those objects, identifying them as transparent features instead of fixed structures, what can also negatively affect mapping and finding the environment. However, the walls can become transparent not only because of the black color but also due to changing light conditions, allowing the user to see holograms through walls (see Figure 51), which was noticed by some participants during navigation. Furthermore, many participants experienced the issue that landmark 5 (fire extinguisher), located at the end of the route, loaded too late or did not load at all for some reason, which forced me to exclude this landmark from the analysis (see Table 8).

Another limitation is that when using the 3D Viewer application to design the navigation route, there is no option to lock the holograms, which creates the problem that the participants could accidentally move or delete the holograms by holding their hands in front of them. For this reason, the participants were instructed to keep their hands down and not touch the holograms during navigation. Note that the safety and experiment instructions can be found in the Appendices.

Figure 47: Correct arrow position (left) and arrow affected by light and reflection conditions (right).

Figure 48: Correct hologram visualization on floor G.

Figure 49: Incorrect hologram visualization on floor H.

Figure 50: Correct hologram visualization on floor H.

Figure 51: Visualization of an arrow from the floor below appearing through the ground.

Another critical issue is that the HoloLens has a limited field of view (FoV). While the human eye can handle about 180°x125° (Kishishita et al., 2014), the HoloLens 2 is restricted to 43°x29° which corresponds to a horizontal FoV of 43° and vertical FoV of 29°(Fu et al., 2024). As a result, the position of the holograms needs to be in the right place towards the user's view, otherwise the arrows and virtual landmarks can be easily overlooked during navigation. The virtual landmarks and arrows were placed close to each other and approximately 1.5 meters above the ground to ensure that everything could be captured by the limited FoV. Nonetheless, based on the video recordings of the navigation sessions from the HoloLens, there were still a few virtual landmarks, such as a Cafeteria Brunnenhof (Landmark 18) and a giant wall painting (Landmark 20), visible for a few seconds during navigation, and therefore overlooked by some participants. An eye-tracking mechanism would be beneficial in those cases and could provide more insights into what users have seen and where the focus lies during navigation. Otherwise, it is difficult to assess why the user did not memorize a specific landmark. For example, it could be that the participant did not remember a landmark because the virtual landmark was overlooked, or it could be that the virtual landmark was recognized but did not have the desired learning effect.

The following table summarizes all errors that occurred during navigation. The errors are collected based on the video recordings from the HoloLens and the Empatica E4 measurements.

Table 8: Summary of all navigation issues.

Error Type	**Description**	**Total Number of Errors**	**Number of Errors caused by fire extinguisher (Landmark 5)**
Error_0	Wormhole issue	2	0
Error_1	The hologram (virtual landmark or holographic arrow) did not show up	32	21
Error_2	Wrong turn because the holographic arrow did not show up	7	0
Error_3	Wrong turn because the holographic arrow was overlooked	3	0
Error_4	Environmental changes (Landmark 10 was removed due to an event)	7	0
No video	Failed to record the video	2	2
E4	Measurement errors of Empatica E4 wristband	6	-

The table shows that the most frequent error refers to the technical issue of not visualizing the holograms, most of them were caused by the fire extinguisher (landmark 5). Subsequently, to reduce the number of errors, landmark 5 and the corresponding intersection were removed from the analysis. However, the other errors were not treated due to their complexity and time limitations. Ideally, the d-prime value for the participants who have turned the wrong way or have encountered environmental changes must be calculated separately because correcting the participants during navigation can increase their spatial knowledge at specific landmarks and intersections. Lastly, the Empatica E4 wristband had technical issues measuring the data for 6 participants. However, these six sessions were removed from the analysis.

5.4 HoloLens Tipps

In my opinion, the user experience with the HoloLens can be improved by considering a few key points for future research. First, the functions “Remove nearby Holograms” and “Remove all holograms” should be applied to reset the device’s knowledge of all space, ensuring correct spatial mapping of the environment. Secondly, similar areas should be avoided to prevent the wormhole issue. However, if this is not possible, the environment can be modified by opening doors on one floor and closing doors on the other floor, which can help to create different-looking floors based on my experience. If the wormhole issue occurs, the device should be turned off immediately to prevent spatial merging of different locations and avoid further visualization issues. The device should then be restarted from a reliable reference position, where it can recognize the environment well again. Furthermore, the LandMarkAR application should be used instead of the 3D Viewer application for several reasons. First, it has more design options for the holograms, including color and precise position with angle rotation. Secondly, it can simplify the experiment setup, allowing to switch between projects, which is very useful for between-subjects experiments. Lastly, it features a spatial anchors mechanism, ensuring a more precise hologram position, which may avoid many position-related issues.

5.5 Suggestions for Future Research

On the one hand, the data obtained from this research can serve as a starting point for further investigation, including post-hoc analysis of significant interaction effects, examination of other fixed variables interactions, and conducting a more detailed analysis of the Empatica E4 data. On the other hand, the results of this work emphasize several directions for future research in this field.

One important direction is to embed eye-tracking technology and repeat or conduct a similar experiment to gather more information about the user’s attention within the MR environment. This will help to understand whether the user focuses more on the holographic arrows, the virtual landmarks, or other elements in the physical environment during navigation. Subsequently, this knowledge will assist in identifying the optimal position for virtual landmarks and navigation aids that fit within the limited FoV of the HoloLens. The HoloLens has an eye-tracking feature built-in. However, extracting the gaze data from the HoloLens might not be an easy task and would require creating a specific application for this use case.

Additionally, the results suggest that wall objects may benefit more from the virtual landmark design compared to the 3D objects. Further research is required to assess whether augmenting 3D objects is necessary, as they might be remembered more easily than wall objects. Moreover, the results indicate a potential increase in mental workload due to the presence of virtual landmarks. It would be interesting to examine how the number of virtual landmarks or holographic arrows will affect the cognitive load during navigation.

Lastly, experimenting with alternative designs, such as hologram animations and color variations, can expand the design options and provide valuable insight into which design works best in maximizing the user’s attention on a specific object and enhancing spatial learning during navigation.

6 Conclusion

The main goal of this study was to test whether implementing virtual landmarks in front of physical landmarks increases the awareness of the physical environment and enhances spatial learning during indoor navigation in MR using Microsoft HoloLens 2. Additionally, the thesis should provide insight into how this design affects the workload during navigation in the MR environment and the emotional stress when solving the post-navigational questionnaires.

The results show a significant difference in spatial learning when integrating virtual landmarks as symbolic recreation in front of the physical landmarks for the MR indoor navigation environment, compared to navigation with only physical landmarks. The virtual landmark group shows a significant increase in spatial learning. However, this effect is only related to the landmark knowledge acquisition. The route knowledge, on the other hand, indicates no statistical difference between the two groups and requires further examination in future studies.

Additionally, it was analyzed if this design had a different effect depending on the landmark type, which was divided into 3D objects and wall objects. By comparing the landmark type, the results show a significant difference between the 3D objects and wall objects, suggesting that 3D objects are noticed better than wall objects. The results also highlight a significant interaction effect between landmark type and the group on spatial knowledge acquisition, including landmark and route knowledge. This suggests that landmarks characterized as wall objects (e.g., wall signs, information boards, pictures) may become more memorable by displaying virtual landmarks in front of them and that 3D objects do not require further augmentation. However, a post-hoc analysis is needed to confirm this statistical significance. More studies should explore this direction to provide valuable information on whether an object requires a virtual augmentation.

No clear evidence has been found that virtual landmarks increase the workload during navigation. The results show no significant difference in the average amplitudes and the number of identified skin conductance response peaks during navigation between the group navigated with virtual landmarks and the group navigated without them. There is also no significant difference in the NASA-TLX score between the two groups. Although the NASA-TLX indicates no significant difference, there is a slight trend that suggests that virtual landmarks can potentially increase the workload during navigation, indicating that further research should be conducted. Finally, using the virtual landmark in navigation does not affect emotional stress, such as a lower stress level when solving the post-navigational questionnaires.

In summary, the proposed design shows improvement in spatial learning performance and situational awareness of the physical environment and emphasizes that it could be integrated in practical examples for indoor navigation. In addition, it highlights that further studies with eye tracking are required to analyze the user's attention, identify the optimal position for holographic navigation aids or virtual landmarks, and test the robustness of the design in terms of the number of virtual landmarks, as too many holograms could lead to a potential workload overload. Although this technology can provide a unique way for indoor wayfinding in the future, much work still needs to be done regarding position-related issues, limited FoV, and finding the optimal design to maximize spatial learning acquisition and situational awareness for indoor wayfinding.

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Appendices

A. List of Landmarks

Figure 52: Landmark 1.

Landmark 1

Landmark 1 is a 3D model of the Zermatter Alps, representing the alpinistic pioneer region during the last glacial maximum. It is a part of the relief exhibition at the Institute of Geography and is located on floor K in the Y25 building.

- Landmark type: 3D Object
- Not visible during navigation

Figure 53: Landmark 2.

Landmark 2

Landmark 2 is a wooden information board with various flyers about evolutionary biology located next to room Y25-G-11.

- Landmark type: Wall Object
- Not visible during navigation

Figure 54: Landmark 3.

Landmark 3

Landmark 3 is a small glass exhibition box containing examples of various mechanical models, such as orbital models, wireframe models, skeletal models, biochemical models, etc. Three similar exhibition boxes are positioned next to each other on floor H in building Y13 in front of the internal post counter (Y13-H-01).

- Landmark type: 3D Object
- Visible during navigation

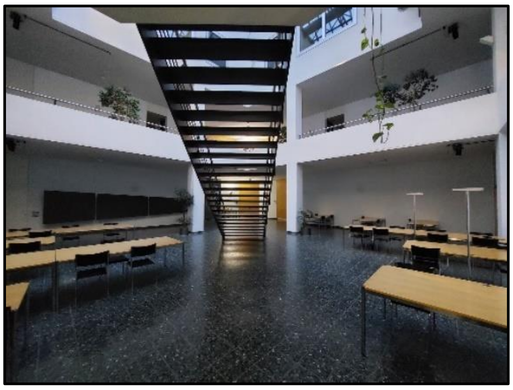


Figure 55: Landmark 4.

Landmark 4

Landmark 4 is a large open space located in the Mathematics Institute (Y27). It is a popular learning area for students.

- Landmark type: 3D Object
- Not visible during navigation

Figure 56: Landmark 5.

Landmark 5

Landmark 5 is a small emergency station equipped with a first aid kit, an information board, a telephone, a fire blanket, two alarm buttons, and two fire extinguishers. It is located directly after the room Y23-F-64. Although there are many emergency stations in the building, this is the only one encountered directly during navigation.

- Landmark type: Wall Object
- Visible during navigation

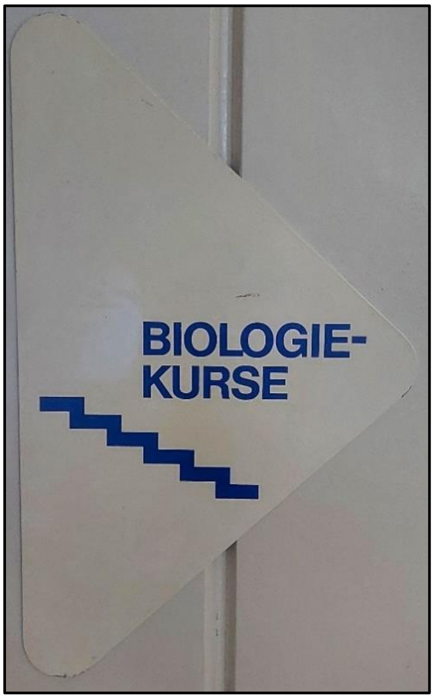


Figure 57: Landmark 6.

Landmark 6

Landmark 6 is a small, flat, white, triangular-shaped sign with blue text indicating the direction to the biology courses. It is mounted on a pillar, which is located on the opposite side of room Y15-G-60a.

- Landmark type: Wall Object
- Not visible during navigation

Figure 58: Landmark 7.

Landmark 7

Landmark 7 is a black coat rack stand located on floor G near the Cafeteria Seerose (Y21) directly in front of the entrance to the Lichthof.

- Landmark type: 3D Object
- Not visible during navigation

Figure 59: Landmark 8.

Landmark 8

Landmark 8 is a large plant located at the transition between buildings Y17 and Y36 at Y17-H-04. Although it is not a unique landmark, as there are other similar plants visible while navigating the route, this is the only plant positioned at an intersection.

- Landmark type: 3D Object
- Visible during navigation

Figure 60: Landmark 9.

Landmark 9

This sand picture shows a section of excavation wall in glacial lake deposits near Diesseenhofen. It is a part of the relief exhibition at the Institute of Geography and is located near room Y25-H-79.

- Landmark type: Wall Object
- Not visible during navigation

Figure 61: Landmark 10.

Landmark 10

Landmark 10 is an exhibition called "Vision Campus Irchel 2050" near room Y04-F-30. It provides insights into how the Irchel Campus has changed and will be modernized in the coming decades up to 2050.

- Landmark type: 3D Object
- Visible during navigation

Figure 62: Landmark 11.

Landmark 11

Landmark 11 is a two-display wall installation providing important information for students of the Institute of Physiology. The landmark is located near the bathroom Y23-F-13, hanging on a brick wall.

- Landmark type: Wall Object
- Visible during navigation

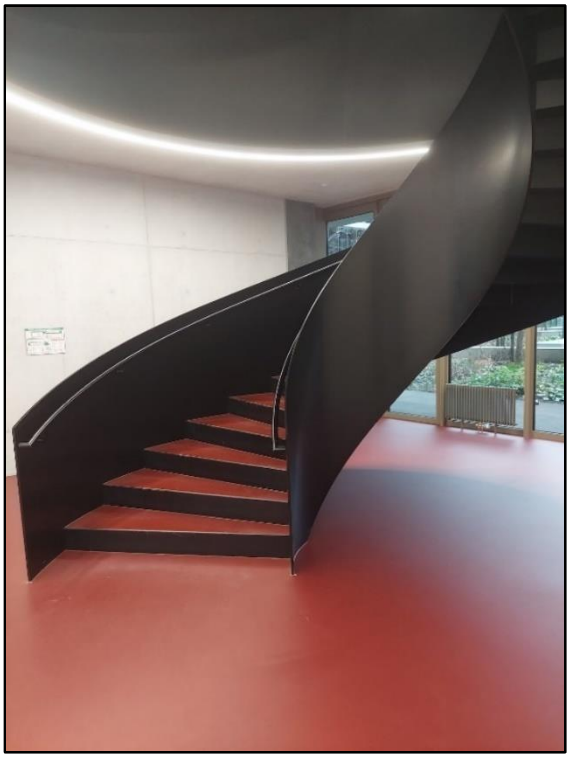


Figure 63: Landmark 12.

Landmark 12

Landmark 12 is a red-black staircase in the Institute of Chemistry (Y38). This staircase is unique due to its bright red color and is the only red staircase encountered during navigation along the route.

- Landmark type: 3D Object
- Visible during navigation

Figure 64: Landmark 13.

Landmark 13

Landmark 13 is a small exhibition of various 3D models created using Additive Manufacturing Technologies (3D printing) by the Department of Biochemistry of the UZH. It is located near the bathroom Y25-H-05.

- Landmark type: 3D Object
- Not visible during navigation

Figure 65: Landmark 14.

Landmark 14

Landmark 14 is a three-display wall installation providing information about publications and seminars of the Institute of Physiology. The landmark is located on the opposite side of room Y23-K-06.

- Landmark type: Wall Object
- Not visible during navigation

Figure 66: Landmark 15.

Landmark 15

Landmark 15 is a small, flat, orange, triangular-shaped sign with blue text indicating the direction to the biology course rooms. It is mounted on a wooden wall near room Y04-F-30.

- Landmark type: Wall Object
- Visible during navigation

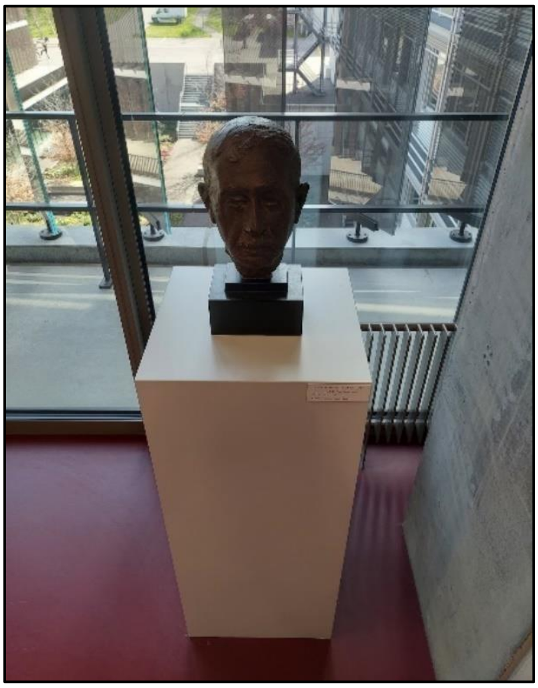


Figure 67: Landmark 16.

Landmark 16

Landmark 16 is a bronze bust of Prof. Dr. Paul Karrer, created in 1959 by Hermann Hubacher and located in the corner by the windows near room Y38-K-03. Paul Karrer[16] studied, taught, and researched at the Institute of Chemistry in Zurich. He worked on plant pigments and researched vitamins and was awarded the Nobel Prize in Chemistry in 1937.

- Landmark type: 3D Object
- Not visible during navigation


Figure 68: Landmark 17.

Landmark 17

Landmark 17 consists of white, wall-mounted lockers located near the restroom Y15-G-15. These lockers differ from others encountered along the route and can be considered a unique landmark.

- Landmark type: Wall Object
- Visible during navigation


Figure 69: Landmark 18.

Landmark 18

Landmark 18 is the Cafeteria Brunnenhof, which can be found at Y13-G-11.

- Landmark type: 3D Object
- Visible during navigation

[16] https://www.uzh.ch/de/researchinnovation/excellence/nobelprize/karrer.html [05.09.2024]

Figure 70: Landmark 19.

Landmark 19

Landmark 19 consists of red, wall-mounted lockers located near room Y24-G-20. These lockers differ from others encountered along the route and can be considered a unique landmark.

- Landmark type: Wall Object
- Not visible during navigation

Figure 71: Landmark 20.

Landmark 20

Landmark 20 is a giant wall painting titled "GENESIS," created by Swiss artist Hermann Alfred Sigg, located near room Y13-F-90.

- Landmark type: Wall Object
- Visible during navigation

B. Virtual Landmarks and Instruction Holograms

Figure 72: Virtual representation of physical landmark 17.

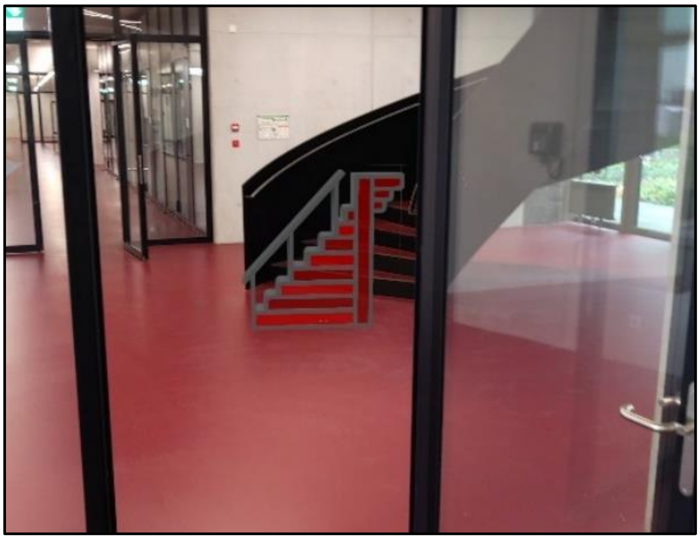


Figure 73: Virtual representation of physical landmark 12.

Figure 74: Virtual representation of physical landmark 8.

Figure 75: Virtual representation of physical landmark 3.

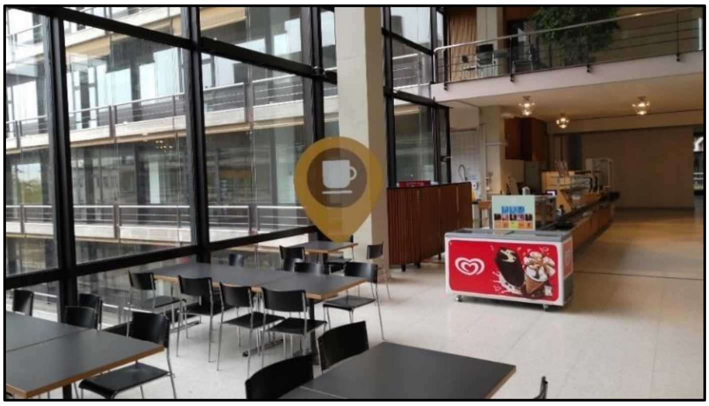


Figure 76: Virtual representation of physical landmark 18.

Figure 77: Virtual representation of physical landmark 20.

Figure 78: Virtual representation of physical landmark 10.

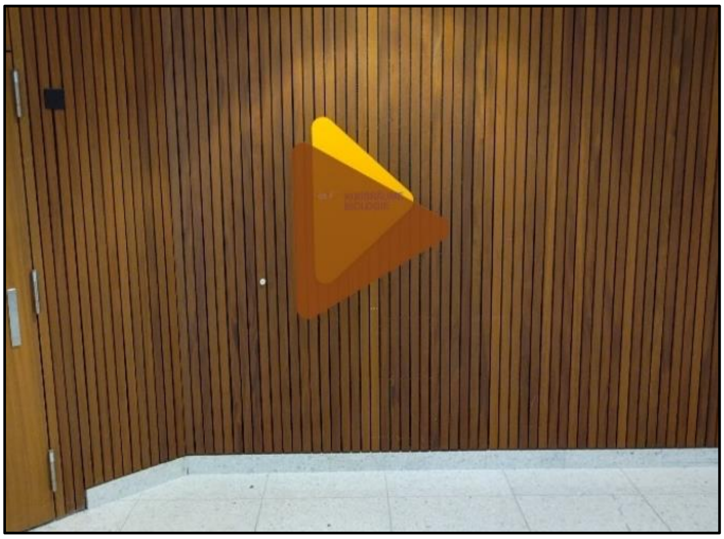


Figure 79: Virtual representation of physical landmark 15.

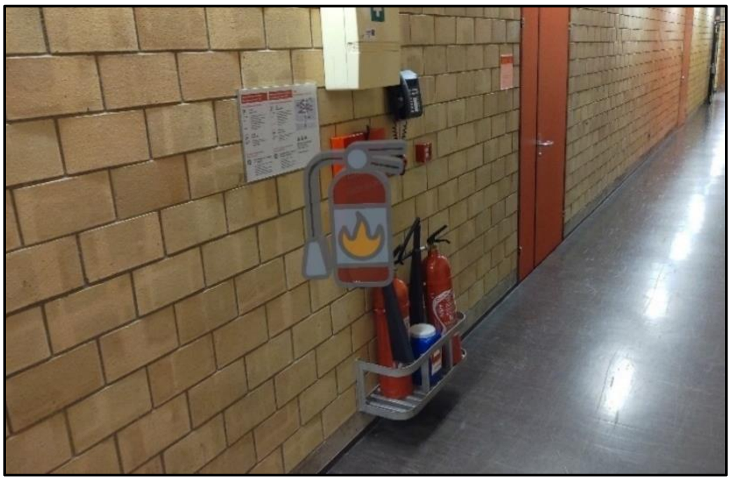


Figure 80: Virtual representation of physical landmark 5.

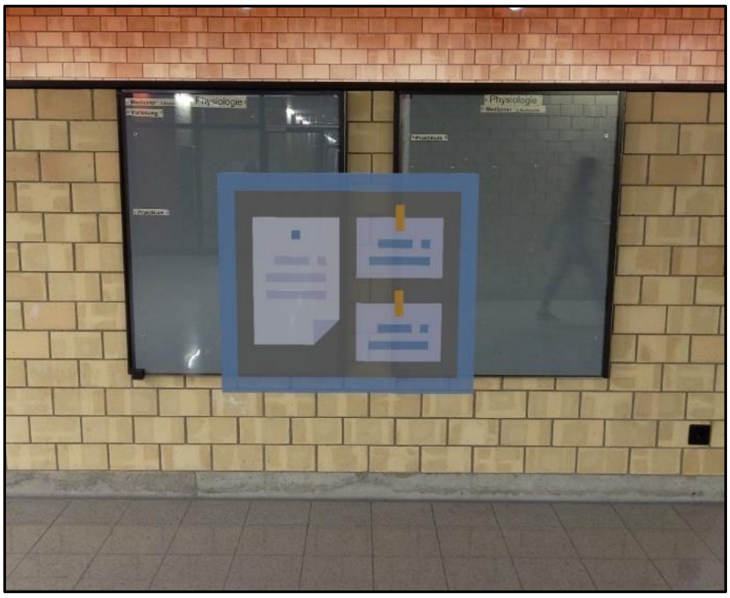


Figure 81: Virtual representation of physical landmark 11.

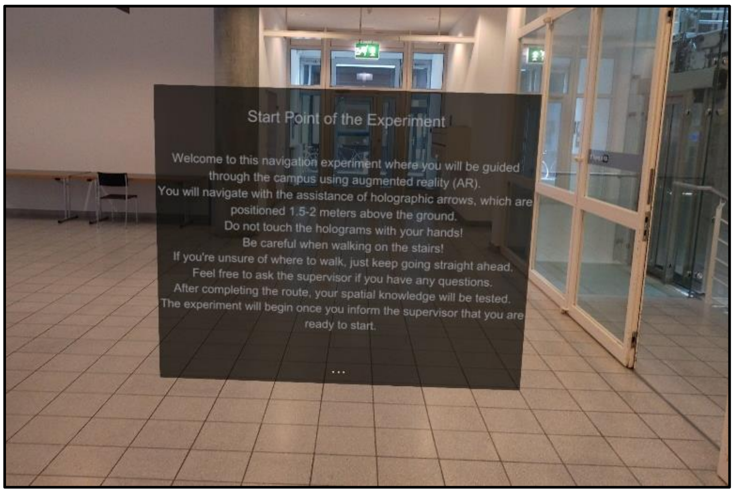


Figure 82: Start point hologram.

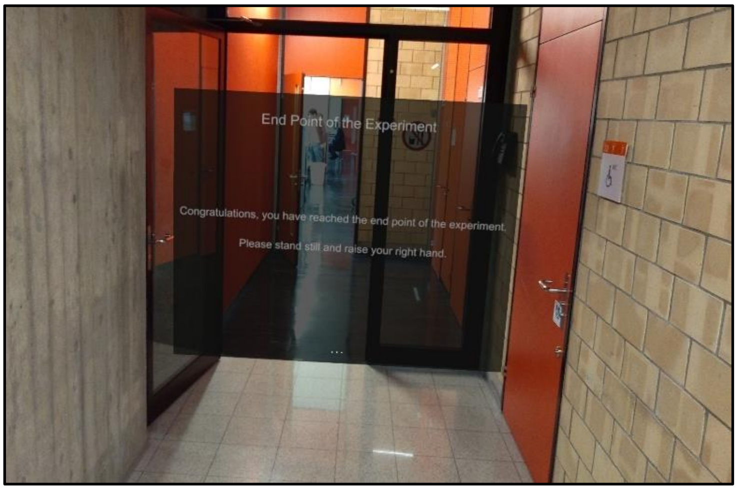


Figure 83: End point hologram.

C. Intersections

Figure 84: Intersection 1 at Y13-F-90.

Figure 85: Intersection 2 at Y04-F-30.

Figure 86: Intersection 3 at Y23-F-13.

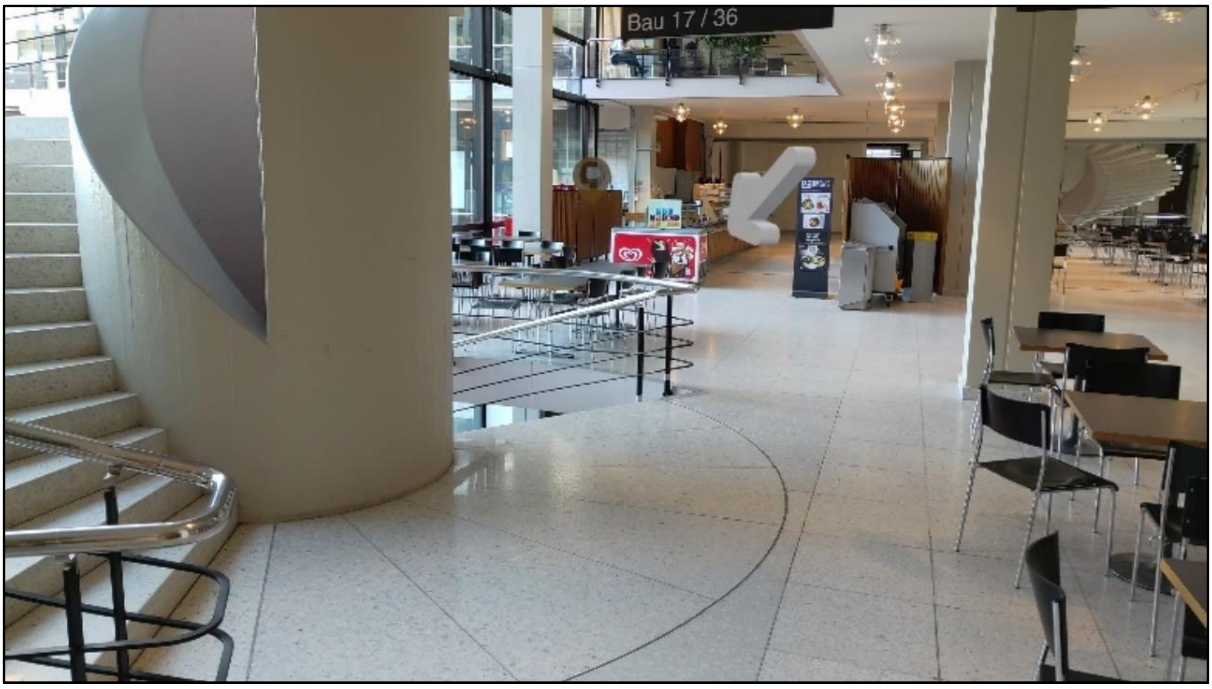


Figure 87: Intersection 4 at Y13-G-11.

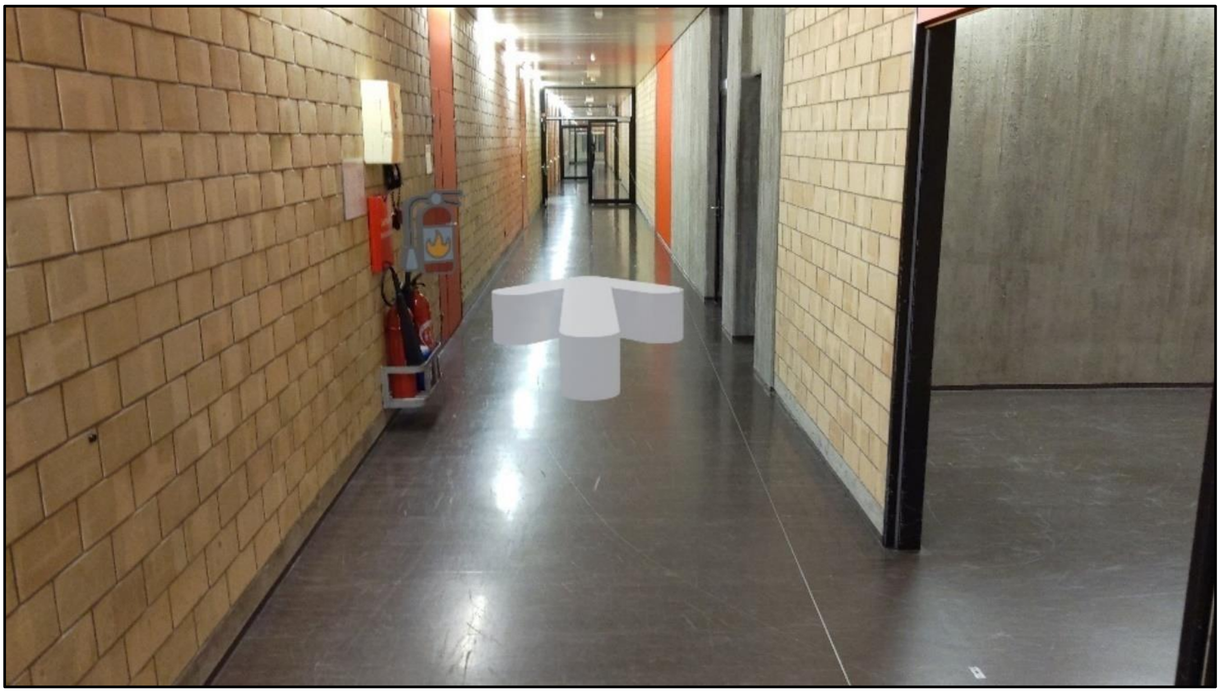


Figure 88: Intersection 5 at Y23-F-64.

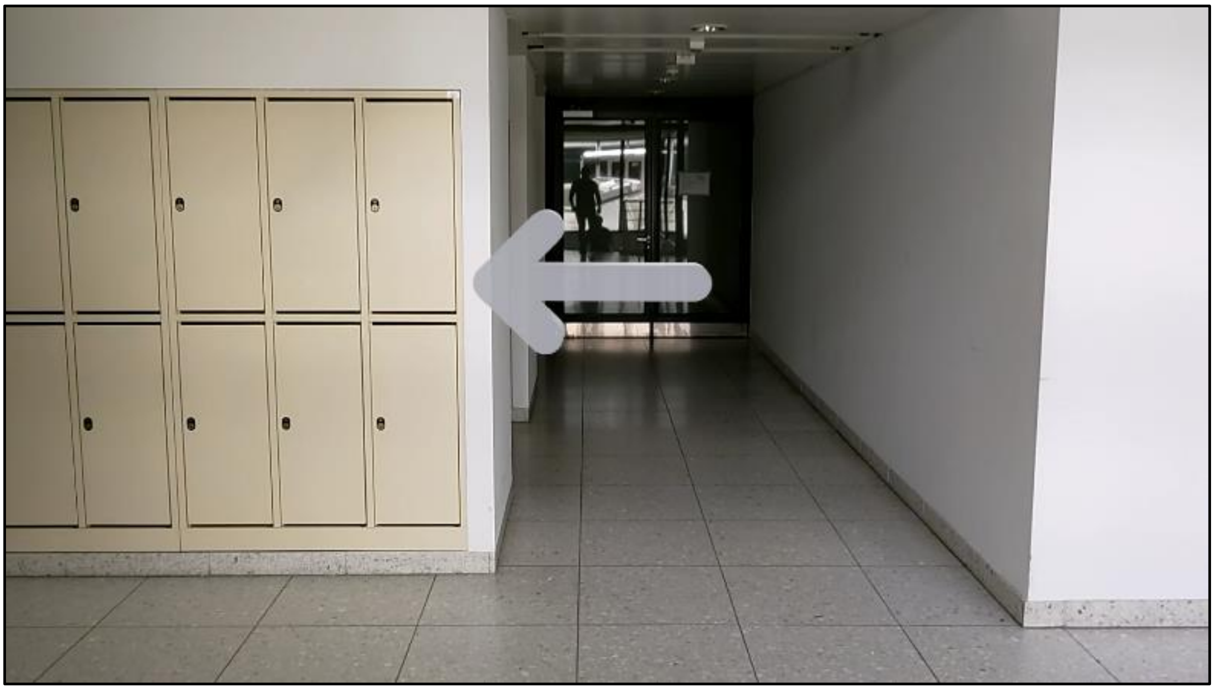


Figure 89: Intersection 6 at Y15-G-15.

Figure 90: Intersection 7 at Y13-H-01.

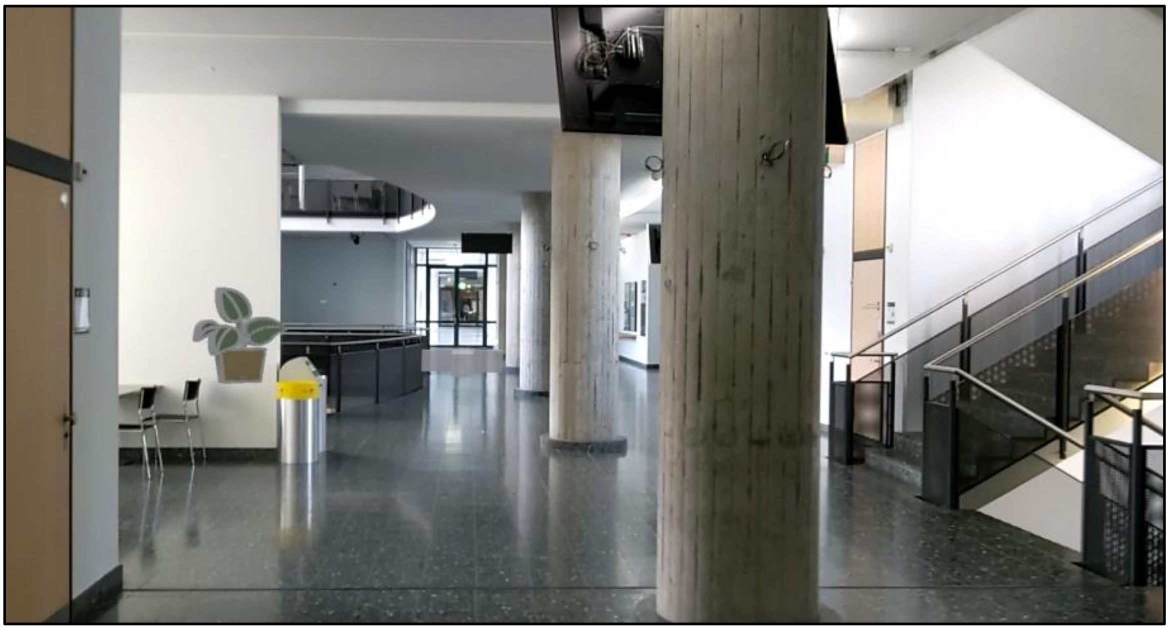


Figure 91: Intersection 8 at Y17-H-04.

Figure 92: Intersection 9 at Y38 floor H.

D. Experiment Registration Formular

Experiment Registration: Indoor Navigation using the Microsoft HoloLens 2

Thank you for your interest in participating the navigation experiment. Please fill out the following form with your basic information to participate in the navigation experiment at the Irchel Campus of the University of Zurich. Detailed information regarding available time slots will be sent to you via email at a later point.

Note: All data will be kept strictly confidential. No information will be published in this study that allows any conclusions to be drawn about you as a person.

If you have any further questions you can contact me at: E-Mail: aleksei.ilchenko@uzh.ch, Tel: +4178 882 00 10

* Gibt eine erforderliche Frage an

1. Full Name *

2. Age *

3. Gender *

Markieren Sie nur ein Oval.

- Male
- Female
- Other

4. Email *

5. Phone Number *

Dieser Inhalt wurde nicht von Google erstellt und wird von Google auch nicht unterstützt.

Google Formulare

E. Santa Barbara Sense-of-Direction Scale

SANTA BARBARA SENSE-OF-DIRECTION SCALE

The following statements ask you about your spatial and navigational abilities, preferences, and experiences. After each statement, you should choose a number to indicate your level of agreement with the statement. Choose "1" if you strongly agree that the statement applies to you, "7" if you strongly disagree, or some number in between if your agreement is intermediate. Choose "4" if you neither agree nor disagree.

Note: All data will be kept strictly confidential. No information will be published in this study that allows any conclusions to be drawn about you as a person.

* Gibt eine erforderliche Frage an

1. Full Name *

2. 1. I am very good at giving directions *

Markieren Sie nur ein Oval.

	1	2	3	4	5	6	7	
stro	◯	◯	◯	◯	◯	◯	◯	strongly disagree

3. 2. I have a poor memory for where I left things. *

Markieren Sie nur ein Oval.

	1	2	3	4	5	6	7	
stro	◯	◯	◯	◯	◯	◯	◯	strongly disagree

4. 3. I am very good at judging distances. *

Markieren Sie nur ein Oval.

	1	2	3	4	5	6	7	
stro	◯	◯	◯	◯	◯	◯	◯	strongly disagree

5. 4. My "sense of direction" is very good. *

Markieren Sie nur ein Oval.

	1	2	3	4	5	6	7	
stro	◯	◯	◯	◯	◯	◯	◯	strongly disagree

6. 5. I tend to think of my environment in terms of cardinal directions (N, S, E, W). *

Markieren Sie nur ein Oval.

	1	2	3	4	5	6	7	
stro	◯	◯	◯	◯	◯	◯	◯	strongly disagree

7. 6. I very easily get lost in a new city. *

Markieren Sie nur ein Oval.

	1	2	3	4	5	6	7	
stro	◯	◯	◯	◯	◯	◯	◯	strongly disagree

8. 7. I enjoy reading maps. *

Markieren Sie nur ein Oval.

	1	2	3	4	5	6	7	
stro	◯	◯	◯	◯	◯	◯	◯	strongly disagree

9. 8. I have trouble understanding directions. *

Markieren Sie nur ein Oval.

	1	2	3	4	5	6	7	
stro	◯	◯	◯	◯	◯	◯	◯	strongly disagree

10. 9. I am very good at reading maps. *

Markieren Sie nur ein Oval.

	1	2	3	4	5	6	7	
stro	◯	◯	◯	◯	◯	◯	◯	strongly disagree

11. 10. I don't remember routes very well while riding as a passenger in a car. *

Markieren Sie nur ein Oval.

	1	2	3	4	5	6	7	
stro	◯	◯	◯	◯	◯	◯	◯	strongly disagree

12. 11. I don't enjoy giving directions. *

Markieren Sie nur ein Oval.

	1	2	3	4	5	6	7	
stro	◯	◯	◯	◯	◯	◯	◯	strongly disagree

13. 12. It's not important to me to know where I am. *

Markieren Sie nur ein Oval.

	1	2	3	4	5	6	7	
stro	◯	◯	◯	◯	◯	◯	◯	strongly disagree

14. 13. I usually let someone else do the navigational planning for long trips. *

Markieren Sie nur ein Oval.

	1	2	3	4	5	6	7	
stro	◯	◯	◯	◯	◯	◯	◯	strongly disagree

15. 14. I can usually remember a new route after I have traveled it only once. *

Markieren Sie nur ein Oval.

	1	2	3	4	5	6	7	
stro	◯	◯	◯	◯	◯	◯	◯	strongly disagree

16. 15. I don't have a very good "mental map" of my environment. *

Markieren Sie nur ein Oval.

	1	2	3	4	5	6	7	
stro	◯	◯	◯	◯	◯	◯	◯	strongly disagree

F. Landmark Knowledge Test

Landmark Knowledge Test

In this section, your landmark knowledge will be tested. Please look at the following images. For each one, indicate whether you saw this landmark while navigating the route. Keep in mind that these **images have been randomized** and do not appear in the order in which you may have encountered them during your navigation.

Note: All data will be kept strictly confidential. No information will be published in this study that allows any conclusions to be drawn about you as a person.

* Gibt eine erforderliche Frage an

1. Participant ID *

(The study supervisor will enter this information for you. No input required.)

2. Landmark 1 *

Markieren Sie nur ein Oval.

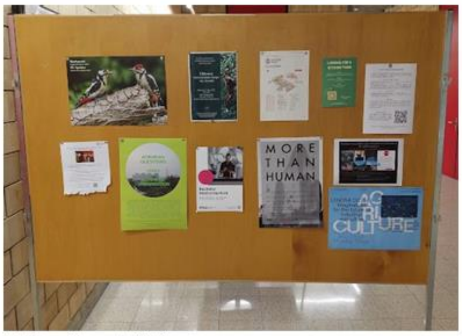
- Yes, I saw this landmark.
- No, I did not see this landmark.

3. Landmark 1: Please indicate how confident you are in your answer. *

Markieren Sie nur ein Oval.

	1	2	3	4	5	
Very	◯	◯	◯	◯	◯	Very sure

4. Landmark 2 *



Markieren Sie nur ein Oval.

- Yes, I saw this landmark.
- No, I did not see this landmark.

5. Landmark 2: Please indicate how confident you are in your answer. *

Markieren Sie nur ein Oval.

	1	2	3	4	5	
Very	◯	◯	◯	◯	◯	Very sure

6. Landmark 3 *

Markieren Sie nur ein Oval.

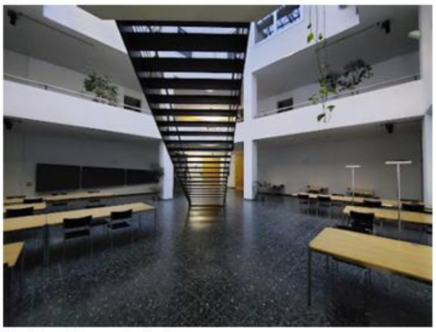
- Yes, I saw this landmark.
- No, I did not see this landmark.

7. Landmark 3: Please indicate how confident you are in your answer. *

Markieren Sie nur ein Oval.

	1	2	3	4	5	
Very	◯	◯	◯	◯	◯	Very sure

8. Landmark 4 *



Markieren Sie nur ein Oval.

- Yes, I saw this landmark.
- No, I did not see this landmark.

9. Landmark 4: Please indicate how confident you are in your answer. *

Markieren Sie nur ein Oval.

	1	2	3	4	5	
Very	◯	◯	◯	◯	◯	Very sure

10. Landmark 5 *

Markieren Sie nur ein Oval.

◯ Yes, I saw this landmark.
◯ No, I did not see this landmark.

11. Landmark 5: Please indicate how confident you are in your answer. *

Markieren Sie nur ein Oval.

	1	2	3	4	5	
Very	◯	◯	◯	◯	◯	Very sure

12. Landmark 6 *

Markieren Sie nur ein Oval.

◯ Yes, I saw this landmark.
◯ No, I did not see this landmark.

13. Landmark 6: Please indicate how confident you are in your answer. *

Markieren Sie nur ein Oval.

	1	2	3	4	5	
Very	◯	◯	◯	◯	◯	Very sure

14. Landmark 7 *

Markieren Sie nur ein Oval.

◯ Yes, I saw this landmark.
◯ No, I did not see this landmark.

15. Landmark 7: Please indicate how confident you are in your answer. *

Markieren Sie nur ein Oval.

	1	2	3	4	5	
Very	◯	◯	◯	◯	◯	Very sure

16. Landmark 8 *

Markieren Sie nur ein Oval.

◯ Yes, I saw this landmark.
◯ No, I did not see this landmark.

17. Landmark 8: Please indicate how confident you are in your answer. *

Markieren Sie nur ein Oval.

	1	2	3	4	5	
Very	◯	◯	◯	◯	◯	Very sure

18. Landmark 9 *

Markieren Sie nur ein Oval.

- ◯ Yes, I saw this landmark.
- ◯ No, I did not see this landmark.

19. Landmark 9: Please indicate how confident you are in your answer. *

Markieren Sie nur ein Oval.

	1	2	3	4	5	
Ver	◯	◯	◯	◯	◯	Very sure

20. Landmark 10 *

Markieren Sie nur ein Oval.

- ◯ Yes, I saw this landmark.
- ◯ No, I did not see this landmark.

21. Landmark 10: Please indicate how confident you are in your answer. *

Markieren Sie nur ein Oval.

	1	2	3	4	5	
Ver	◯	◯	◯	◯	◯	Very sure

22. Landmark 11 *

Markieren Sie nur ein Oval.

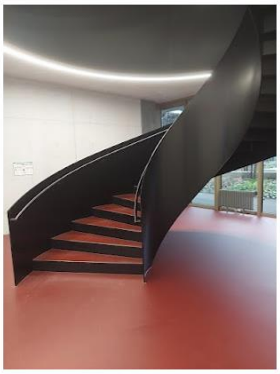
- ◯ Yes, I saw this landmark.
- ◯ No, I did not see this landmark.

23. Landmark 11: Please indicate how confident you are in your answer. *

Markieren Sie nur ein Oval.

	1	2	3	4	5	
Ver	◯	◯	◯	◯	◯	Very sure

24. Landmark 12 *



Markieren Sie nur ein Oval.

- ◯ Yes, I saw this landmark.
- ◯ No, I did not see this landmark.

25. Landmark 12: Please indicate how confident you are in your answer. *

Markieren Sie nur ein Oval.

	1	2	3	4	5	
Ver	◯	◯	◯	◯	◯	Very sure

26. Landmark 13 *

Markieren Sie nur ein Oval.

- Yes, I saw this landmark.
- No, I did not see this landmark.

27. Landmark 13: Please indicate how confident you are in your answer. *

Markieren Sie nur ein Oval.

	1	2	3	4	5	
Very	◯	◯	◯	◯	◯	Very sure

28. Landmark 14 *

Markieren Sie nur ein Oval.

- Yes, I saw this landmark.
- No, I did not see this landmark.

29. Landmark 14: Please indicate how confident you are in your answer. *

Markieren Sie nur ein Oval.

	1	2	3	4	5	
Very	◯	◯	◯	◯	◯	Very sure

30. Landmark 15 *

Markieren Sie nur ein Oval.

- Yes, I saw this landmark.
- No, I did not see this landmark.

31. Landmark 15: Please indicate how confident you are in your answer. *

Markieren Sie nur ein Oval.

	1	2	3	4	5	
Very	◯	◯	◯	◯	◯	Very sure

32. Landmark 16 *

Markieren Sie nur ein Oval.

- Yes, I saw this landmark.
- No, I did not see this landmark.

33. Landmark 16: Please indicate how confident you are in your answer. *

Markieren Sie nur ein Oval.

	1	2	3	4	5	
Very	◯	◯	◯	◯	◯	Very sure

34. Landmark 17 *

Markieren Sie nur ein Oval.

- Yes, I saw this landmark.
- No, I did not see this landmark.

35. Landmark 17: Please indicate how confident you are in your answer. *

Markieren Sie nur ein Oval.

	1	2	3	4	5	
Very	◯	◯	◯	◯	◯	Very sure

36. Landmark 18 *

Markieren Sie nur ein Oval.

- Yes, I saw this landmark.
- No, I did not see this landmark.

37. Landmark 18: Please indicate how confident you are in your answer. *

Markieren Sie nur ein Oval.

	1	2	3	4	5	
Very	◯	◯	◯	◯	◯	Very sure

38. Landmark 19 *

Markieren Sie nur ein Oval.

- Yes, I saw this landmark.
- No, I did not see this landmark.

39. Landmark 19: Please indicate how confident you are in your answer. *

Markieren Sie nur ein Oval.

	1	2	3	4	5	
Very	◯	◯	◯	◯	◯	Very sure

40. Landmark 20 *

Markieren Sie nur ein Oval.

- Yes, I saw this landmark.
- No, I did not see this landmark.

41. Landmark 20: Please indicate how confident you are in your answer. *

Markieren Sie nur ein Oval.

	1	2	3	4	5	
Very	◯	◯	◯	◯	◯	Very sure

G. Route Knowledge Test

Route Knowledge Test

In this section, your route knowledge will be tested. Please look at the following images. For each one, indicate the direction you took at each intersection. Keep in mind that these **images have been randomized** and do not appear in the order in which you may have encountered them during your navigation.

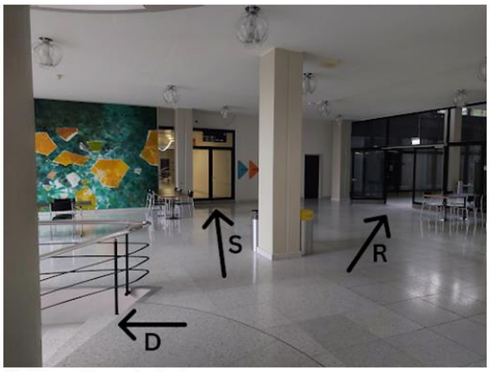
Note: All data will be kept strictly confidential. No information will be published in this study that allows any conclusions to be drawn about you as a person.

* Gibt eine erforderliche Frage an

1. Participant ID *

(The study supervisor will enter this information for you. No input required.)

2. Intersection 1 *



Markieren Sie nur ein Oval.

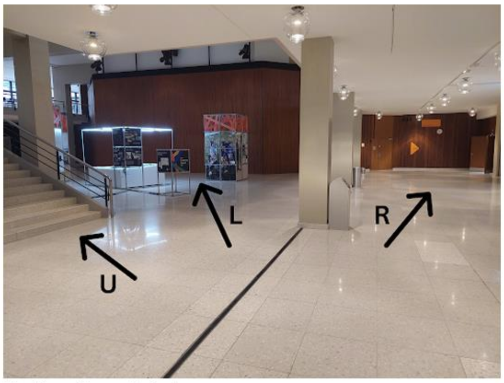
- D (Down)
- S (Straight)
- R (Right)

3. Intersection 1: Please indicate how confident you are in your answer. *

Markieren Sie nur ein Oval.

	1	2	3	4	5	
Very	◯	◯	◯	◯	◯	Very sure

4. Intersection 2 *



Markieren Sie nur ein Oval.

- U (Up)
- L (Left)
- R (Right)

5. Intersection 2: Please indicate how confident you are in your answer. *

Markieren Sie nur ein Oval.

	1	2	3	4	5	
Very	◯	◯	◯	◯	◯	Very sure

6. Intersection 3 *

Markieren Sie nur ein Oval.

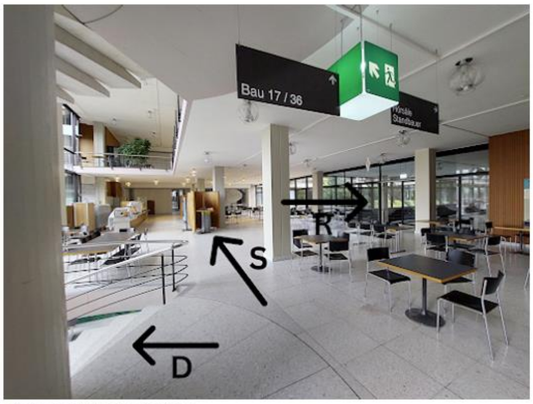
- L (Left)
- R (Right)

7. Intersection 3: Please indicate how confident you are in your answer. *

Markieren Sie nur ein Oval.

	1	2	3	4	5	
Very	◯	◯	◯	◯	◯	Very sure

8. Intersection 4 *



Markieren Sie nur ein Oval.

- D (Down)
- S (Straight)
- R (Right)

9. Intersection 4: Please indicate how confident you are in your answer. *

Markieren Sie nur ein Oval.

	1	2	3	4	5	
Very	◯	◯	◯	◯	◯	Very sure

10. Intersection 5 *

Markieren Sie nur ein Oval.

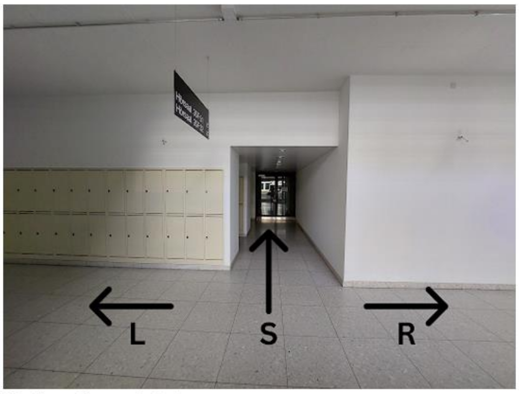
- S (Straight)
- R (Right)

11. Intersection 5: Please indicate how confident you are in your answer.

Markieren Sie nur ein Oval.

	1	2	3	4	5	
Very	◯	◯	◯	◯	◯	Very sure

12. Intersection 6 *



Markieren Sie nur ein Oval.

- L (Left)
- S (Straight)
- R (Right)

13. Intersection 6: Please indicate how confident you are in your answer. *

Markieren Sie nur ein Oval.

	1	2	3	4	5	
Very	◯	◯	◯	◯	◯	Very sure

14. Intersection 7 *

Markieren Sie nur ein Oval.

- S (Straight)
- U (Up)
- D (Down)

15. Intersection 7: Please indicate how confident you are in your answer. *

Markieren Sie nur ein Oval.

	1	2	3	4	5	
Very	◯	◯	◯	◯	◯	Very sure

16. Intersection 8 *

Markieren Sie nur ein Oval.

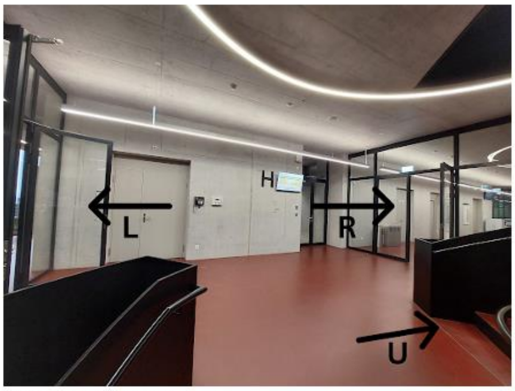
- S (Straight)
- U (Up)
- D (Down)

17. Intersection 8: Please indicate how confident you are in your answer. *

Markieren Sie nur ein Oval.

	1	2	3	4	5	
Very	◯	◯	◯	◯	◯	Very sure

18. Intersection 9 *



Markieren Sie nur ein Oval.

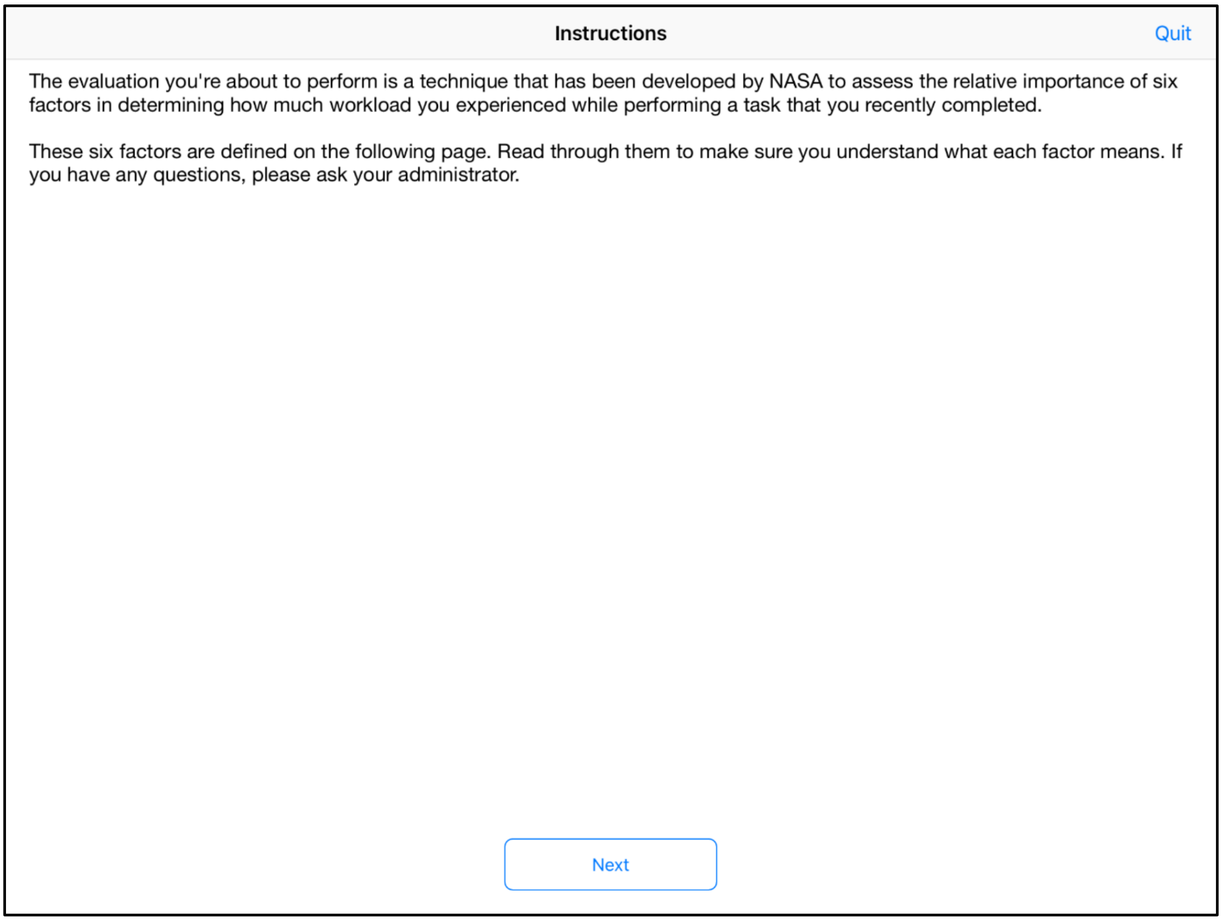
- L (Left)
- R (Right)
- U (Up)

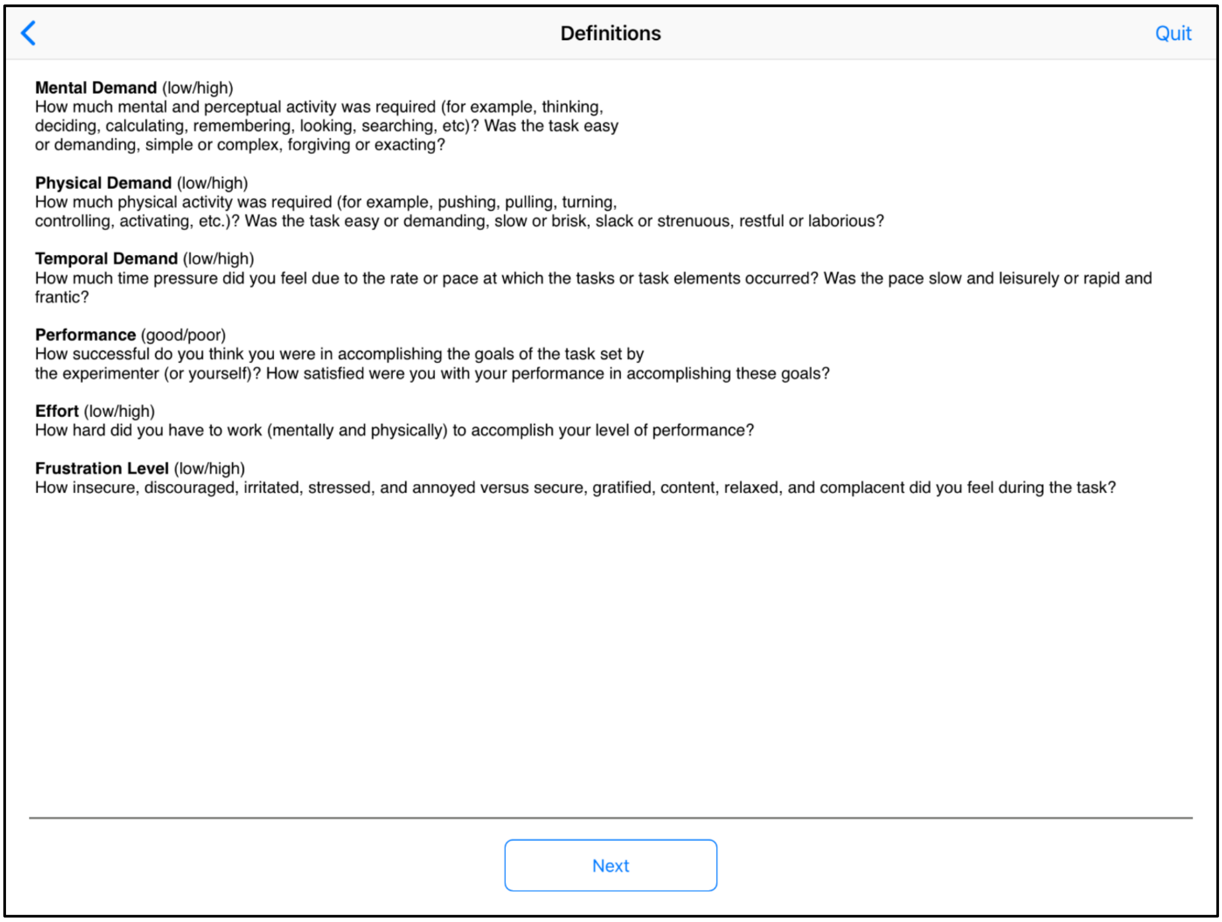
19. Intersection 9: Please indicate how confident you are in your answer. *

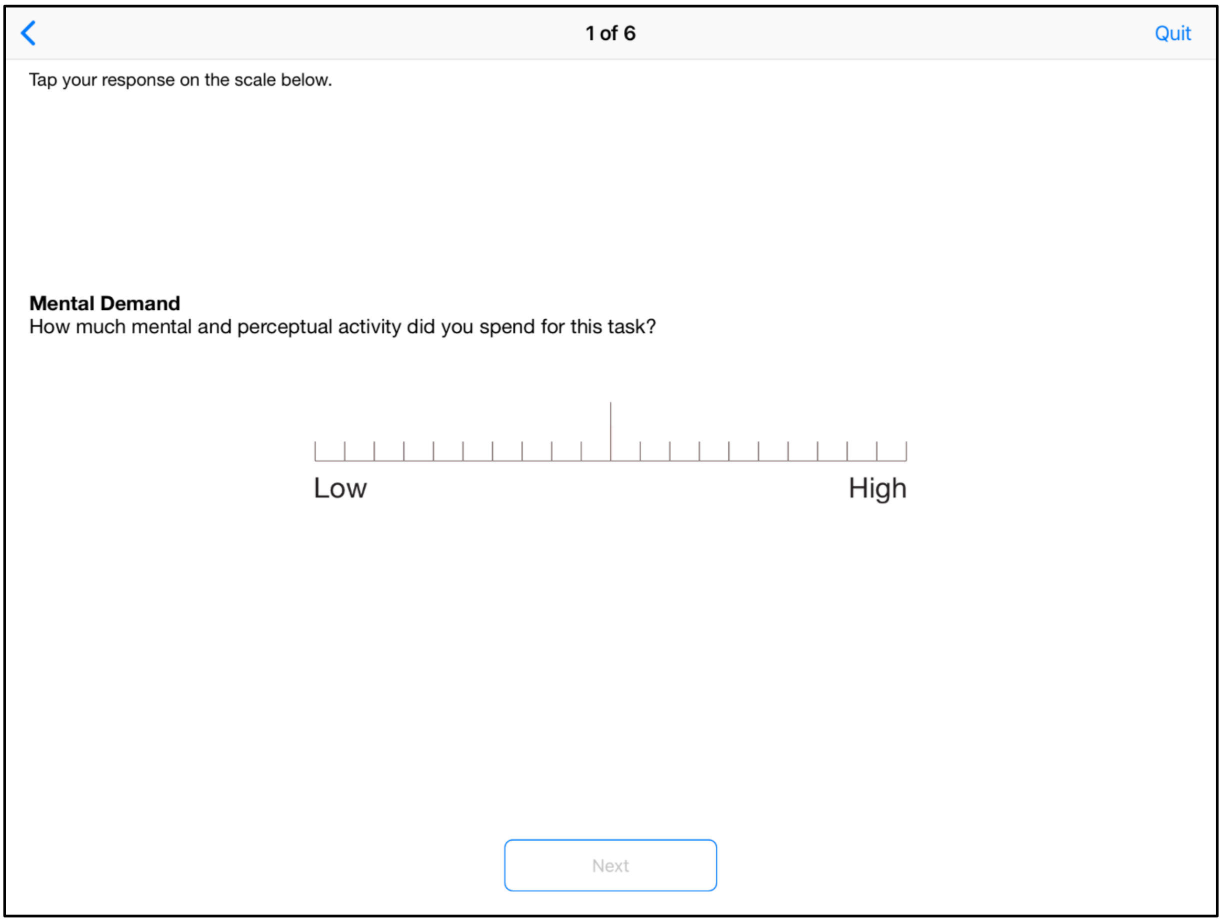
Markieren Sie nur ein Oval.

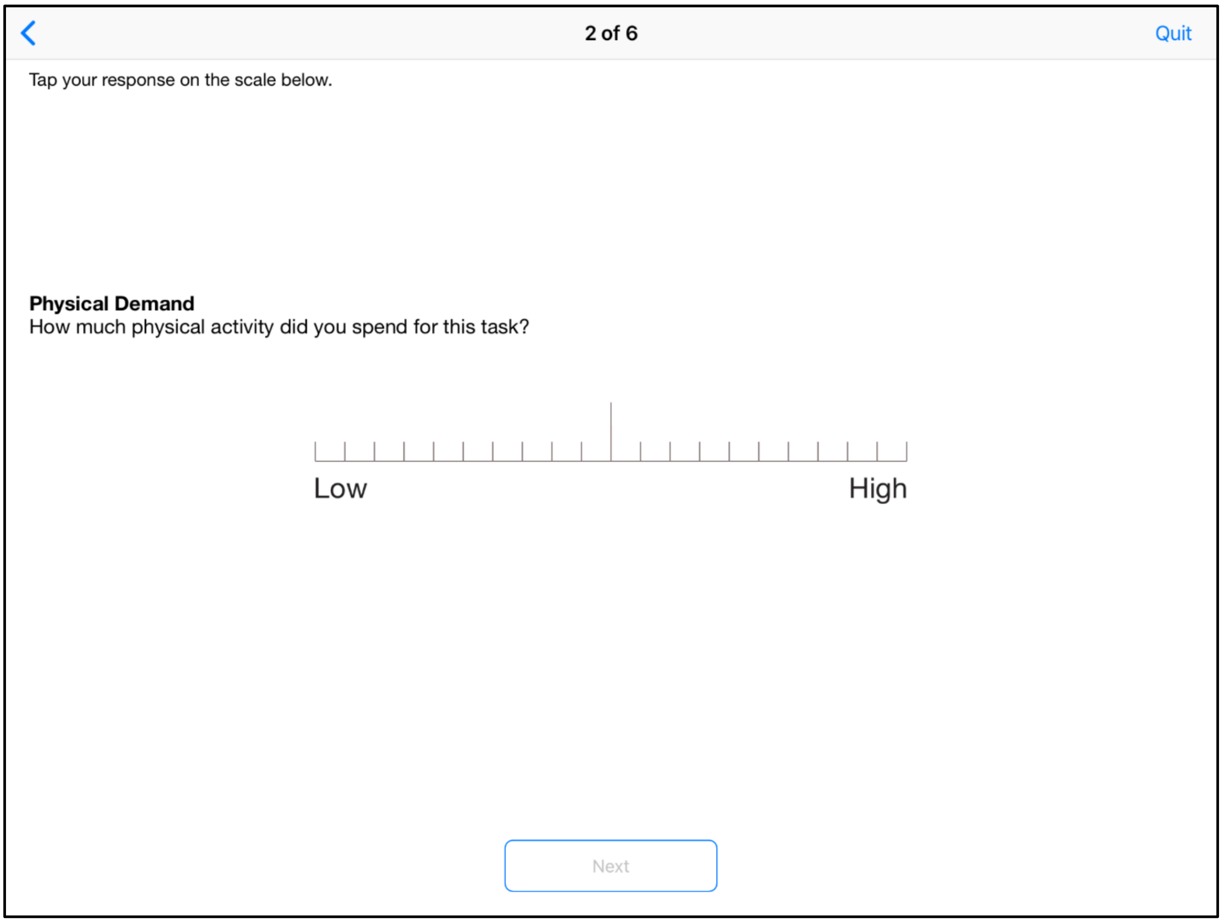
	1	2	3	4	5	
Very	◯	◯	◯	◯	◯	Very sure

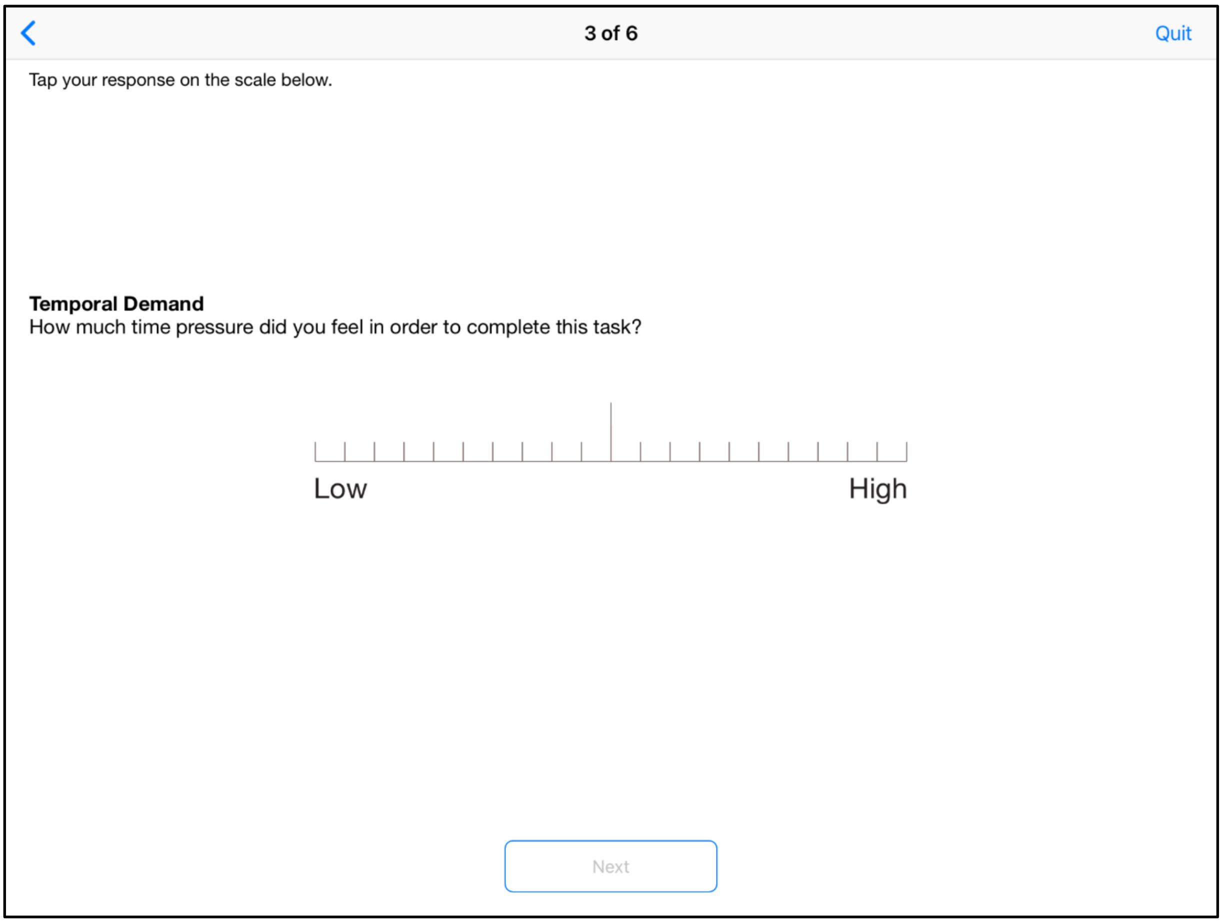
H. NASA Task Load Index Test

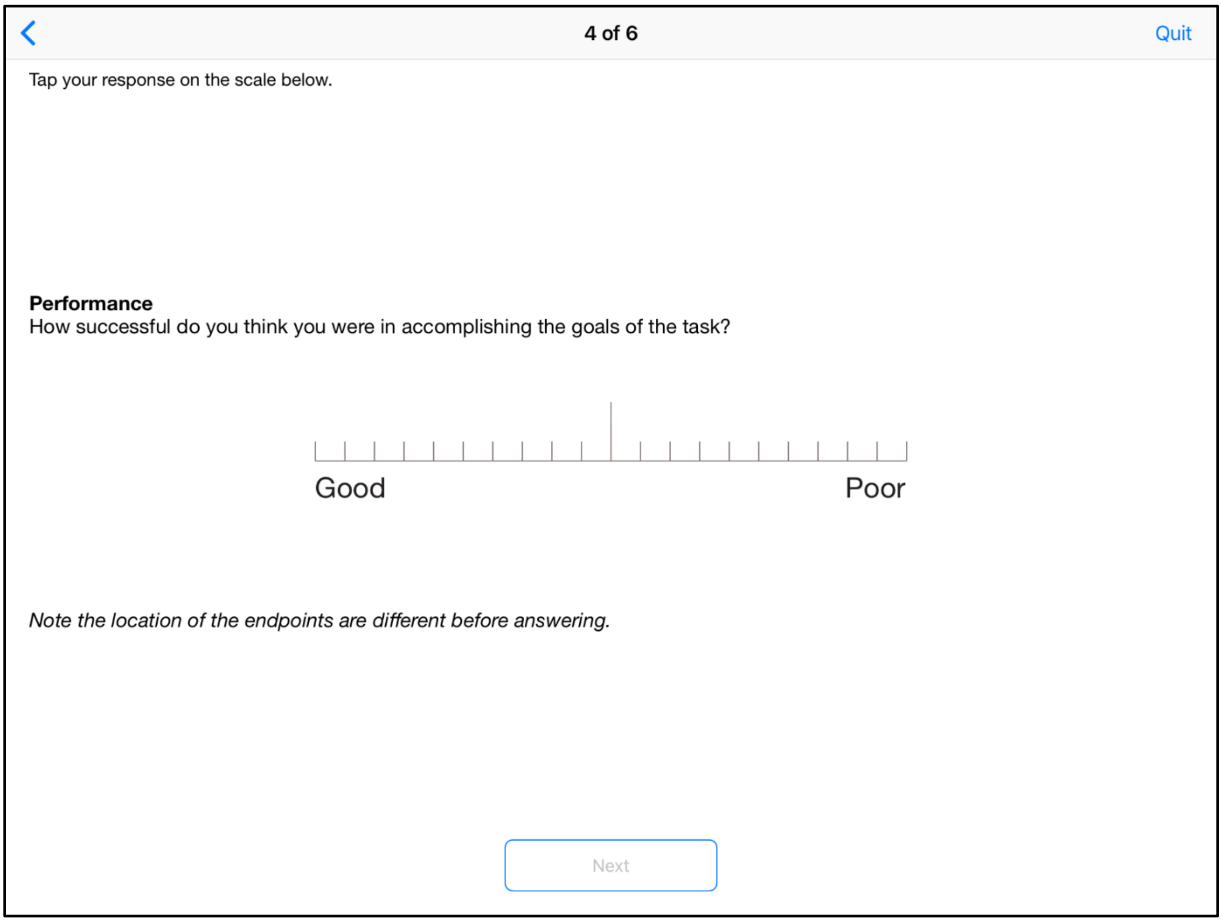


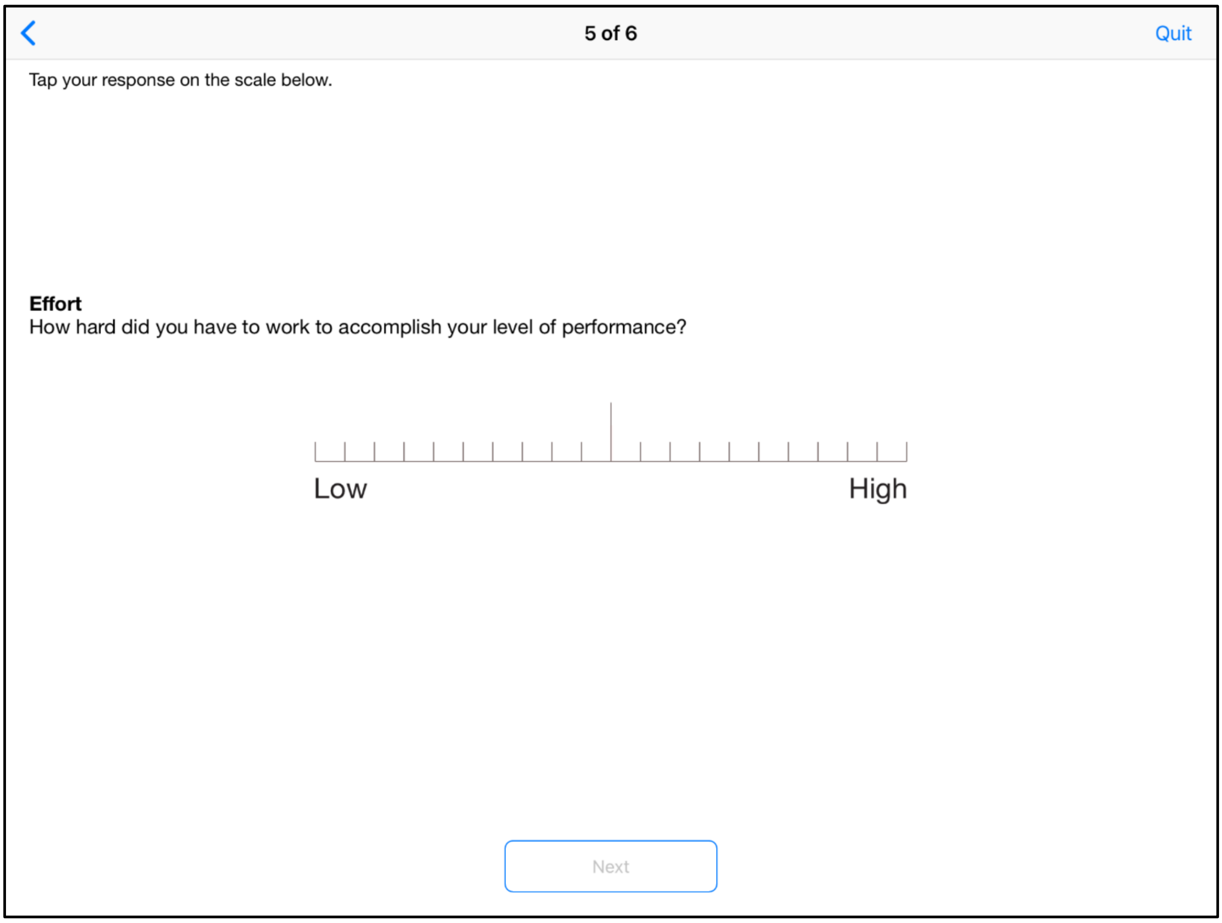


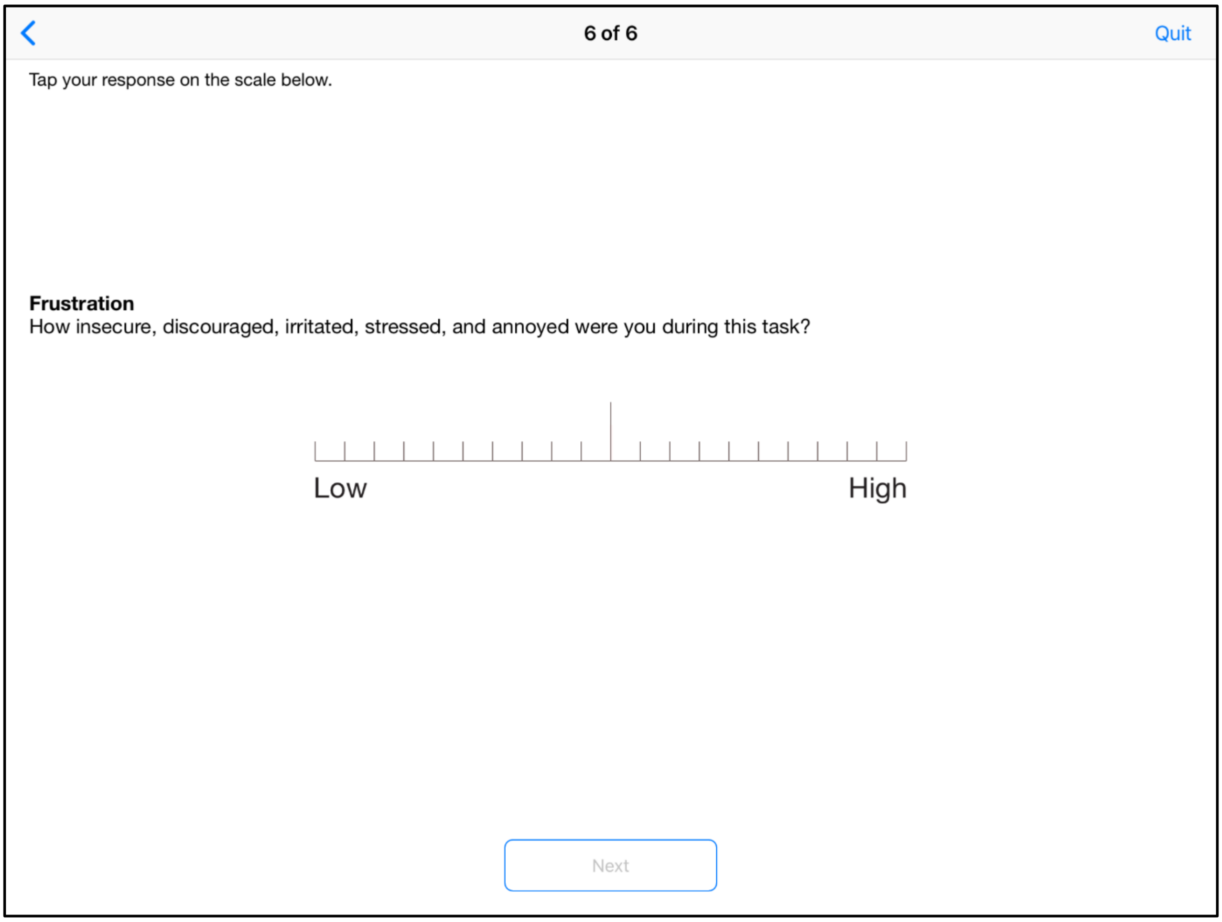

1 of 6
Quit
Tap your response on the scale below.
Mental Demand
How much mental and perceptual activity did you spend for this task?
Low
High
Next


2 of 6
Quit
Tap your response on the scale below.
Physical Demand
How much physical activity did you spend for this task?
Low
High
Next


3 of 6
Quit
Tap your response on the scale below.
Temporal Demand
How much time pressure did you feel in order to complete this task?
Low
High
Next


4 of 6
Quit
Tap your response on the scale below.
Performance
How successful do you think you were in accomplishing the goals of the task?
Good
Poor
Note the location of the endpoints are different before answering.
Next


5 of 6
Quit
Tap your response on the scale below.
Effort
How hard did you have to work to accomplish your level of performance?
Low
High
Next


6 of 6
Quit
Tap your response on the scale below.
Frustration
How insecure, discouraged, irritated, stressed, and annoyed were you during this task?
Low
High
Next

I. Final Questions

Post Navigational Questions

Note: All data will be kept strictly confidential. No information will be published in this study that allows any conclusions to be drawn about you as a person.

* Gibt eine erforderliche Frage an

1. Participant ID *

   (The study supervisor will enter this information for you. No input required.)

   ____

2. I am very familiar with the route. *

   Markieren Sie nur ein Oval.

	1	2	3	4	5	
stro	◯	◯	◯	◯	◯	strongly agree

3. I have much experience using Virtual Reality/Augmented Reality. *

   Markieren Sie nur ein Oval.

	1	2	3	4	5	
stro	◯	◯	◯	◯	◯	strongly agree

4. I felt very comfortable navigating the route using the HoloLens. *

   Markieren Sie nur ein Oval.

	1	2	3	4	5	
stro	◯	◯	◯	◯	◯	strongly agree

5. Feedback/comments? (not mandatory)

   ____

J. Consent Form

Dear participant

You agreed to participate in a study conducted by Aleksei Ilchenko for his master's thesis at the Department of Geography of the University of Zurich.

Contact details of the study supervisor

Aleksei Ilchenko, E-Mail: aleksei.ilchenko@uzh.ch, Tel: +4178 882 00 10

Aim of the study

The aim of the study is to investigate the influence of augmented reality (AR) navigation systems on spatial knowledge formations and on the emotional responses of the participants.

Test procedure

The study consists of three parts. In the first part, you will be asked to provide information about yourself (e.g., age and gender). Then, you will complete a questionnaire about your spatial skills and orientation in space. This part takes place prior to the actual study.

In the second part, you will have to follow a navigation route with the help of an Augmented Reality (AR) navigation system. Before starting the navigation task, we will install and calibrate the Empatica E4 band on your wrist, which you will keep throughout your participation. The visual content displayed on the AR system, including your gesture interactions, will be recorded for analysis purposes. However, no video or photographic recordings of the participants themselves will be made.

In the last part, you will be asked to fill out questionnaires about your acquired spatial knowledge and task mental workload. All collected data will be stored anonymously, and no information that allows any conclusion to be drawn about you as a person will be published in this study.

Voluntary participation

Your participation in this study is entirely voluntary. You may withdraw your consent to participate in this study at any time without providing notice or reason. You may always ask questions about the experiment at all times.

Benefits for the participants

This study offers no direct benefit to the participant.

Data confidentiality

This study involves recording your personal information. All data are coded by replacing the names with a code and are made anonymous. Furthermore, your name will never be used in any reports or publications. All collected data will be kept encrypted and stored on secure media protected by a password only known to researchers listed above.

The personal information provided here is stored for a period of 10 years due to a legal obligation. A local ethics committee may examine the information during this period. All the information is stored in a locked laboratory space and on a highly secure server at the Department of Geography of the University of Zurich.

Costs

The entire study will not incur any direct costs to the participants.

Compensation

The participants will not receive any financial compensation for participating in this study.

Termination of participation

Your participation will be cancelled if you

- are not able (anymore) to understand or adhere to the instructions of the supervisor.
- withdraw your participation. Should you wish to do so after completion, your data will be deleted.

Informed consent

I have been given enough time to read the information sheet on the experiment, and all my questions regarding this experiment have been satisfactorily addressed. In a case where I am unable to read this document or give written consent, I confirm that I have received this information orally. I understand the requirements of the experiment and agree to participate in this study voluntarily.

Place/Date Signature of the participant

____________________________ _____________________________

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

Place/Date	Signature of the experimenter
____________________________	_____________________________

K. Experiment Instructions for Supervisor

Meeting Point (3 min)	• Meet at Blue Cow → navigate to the starting point.
Start Point (10 min)	• Use the toilet and drink water if needed. • Briefly explain the experiment workflow (E4 calibration, HoloLens calibration, navigation, questionnaires). • Sign the consent form. • Put the E4 on the non-dominant hand and start recording. • Define the baseline (2 min sitting with closed eyes and ear protection). • Calibrate the HoloLens. • Provide safety instructions. • Help to start the video recording. • Last chance to ask questions. • No supervisor interaction is allowed.
During the Route (10 min)	• Follow approximately 3 meters behind the participant. • Correct them if they make a wrong turn. • Set time logs on the smartphone.
End Point (2 min)	• Collect the HoloLens from participant. • Stop video recording. • Return to Eye Tracking Lab (take elevator to L).
Questionnaires (20 min)	• Set time logs on the smartphone. • Conduct the Landmark Knowledge Test. • Conduct the Route Knowledge Test. • Conduct the NASA Task Load Index Test. • Conduct the Final Questionnaire. • Stop recording on the Empatica E4. • Thank the participant with chocolate.
Prepare the Next Session (30 min)	• Charge HoloLens if necessary. • Save the obtained data. • Check the route again.

Safety instructions and checks for the supervisor:

- The HoloLens can lose the environment. If this happens, a message will pop up. Stop walking when you see this message, the device will recalibrate the environment. □
- Be very careful when navigating up and down stairs. Look at the steps in front of you. □
- Do not move your head too quickly. □
- Do not touch the holograms with your hands to avoid accidentally deleting them. Walking through the holograms is allowed. □
- The study supervisor will follow you behind, no interaction is allowed. □
- Navigate as you would if you were exploring a new environment. □

L. 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.

Ich erkläre hiermit, dass ich die vorliegende Arbeit selbständig verfasst und die den verwendeten Quellen wörtlich oder inhaltlich entnommenen Stellen als solche kenntlich gemacht habe.

Date

29.09.24

Signature