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Spatial Learning with Mixed Reality-based Navigation

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Abstract

Navigation assistance plays an important role in highly mobile modern life and professional operations. In recent years, navigation services have faced more and more demanding requirements: they should be not only functional but also user-friendly, e.g., adaptive to users' needs and can preserve users' spatial learning ability. The latter requirement originates from a worrisome phenomenon that excessive reliance on navigation may weaken spatial learning ability. Researchers have been seeking possibilities to preserve or improve spatial learning through active intentional, and passive incidental learning during navigation. While intentional learning may result in better spatial memory, incidental learning is more practical in daily navigation. The various emerging indoor positioning technologies, including mixed reality, have provided new opportunities to understand the problems and are potential in complex indoor navigation services. This cumulative thesis tackles the dilemma of learning during navigation and the usability of MR-based navigation.

To explore approaches for the construction of minimal viable MR-based navigation applications dedicated to studying user behavior, the author reviewed the available MR devices, the requirements and influence factors for user studies, and summarized the approaches to building an MR-based navigation application and their application scenarios. The requirements for user study and available sources in the study area should be clarified before building the MR-based navigation application for research purposes.

To understand the influence of the interface on users' spatial memory and to visualize the navigation instructions in a spatial learning-friendly way, the author examined ordinary users' perceptions, proposed using virtual landmarks in MR-based navigation, and collected users' feedback on the interface design concerning spatial learning. The results of user studies suggest that MR-based navigation is both risky and promising for ordinary users' spatial learning. The users might be misled by incorrect virtual visualization, but the virtual landmark can assist their spatial learning.

To understand the relationship between the environment and users' attention, the author analyzed the environmental characteristics that influence people's navigation and conducted an eye-tracking-based user study, which revealed different gaze distributions when navigating in regular and irregular road networks.

The publications involved in the thesis have addressed spatial learning issues during MR-based navigation from the perspectives of ordinary users' perception, interface design, and the influence of the environment. The technological influence on spatial learning during navigation remains to be examined.

Zusammenfassung

Navigationshilfen spielen im hochmobilen modernen Alltag und im Berufsleben eine wichtige Rolle. In den letzten Jahren wurden die Anforderungen an Navigationsdienste immer höher: Diese sollten nicht nur funktional, sondern auch benutzerfreundlich sein, d. h. sich an die Bedürfnisse der Benutzer anpassen und die räumliche Lernfähigkeit der Benutzer erhalten. Die letztgenannte Anforderung geht auf das besorgniserregende Phänomen zurück, dass eine übermäßige Abhängigkeit von Navigation die Fähigkeit zum räumlichen Lernen schwächen kann. Forscher haben nach Möglichkeiten gesucht, das räumliche Lernen durch aktives, absichtliches und passives, zufälliges Lernen während der Navigation zu erhalten oder zu verbessern. Während absichtliches Lernen zu einem besseren räumlichen Gedächtnis führen kann, ist beiläufiges Lernen für die tägliche Navigation praktischer. Die verschiedenen entstehenden Positionierungstechnologien für Innenräume, einschließlich der gemischten Realität, haben neue Möglichkeiten geschaffen, die Probleme und das Potenzial komplexer Navigationsdienste für Innenräume zu verstehen. Diese kumulative Dissertation befasst sich mit dem Dilemma des Lernens während der Navigation und der Benutzerfreundlichkeit von MR-basierter Navigation.

Um Ansätze für die Konstruktion von minimal praktikablen MR-basierten Navigationsanwendungen zur Untersuchung des Nutzerverhaltens zu erforschen, überprüfte die Autorin die verfügbaren MR-Geräte, die Anforderungen und Einflussfaktoren für Nutzerstudien und fasste die Ansätze zur Konstruktion einer MR-basierten Navigationsanwendung und deren Anwendungsszenarien zusammen. Vor der Entwicklung einer MR-basierten Navigationsanwendung für Forschungszwecke sollten die Anforderungen an die Nutzerforschung und die verfügbaren Quellen im Untersuchungsgebiet geklärt werden.

Um den Einfluss der Schnittstelle auf das räumliche Gedächtnis der Nutzer zu verstehen und die Navigationsanweisungen auf eine lernfreundliche Art und Weise zu visualisieren, untersuchte die Autorin die Wahrnehmung normaler Nutzer, schlug die Verwendung virtueller Orientierungspunkte in der MR-basierten Navigation vor und sammelte das Feedback der Nutzer zum Schnittstellendesign hinsichtlich des räumlichen Lernens. Die Ergebnisse der Nutzerstudien deuten darauf hin, dass die MR-basierte Navigation sowohl Risiken birgt als auch vielversprechend für das räumliche Lernen der normalen Nutzer ist. Die Benutzer könnten durch eine falsche virtuelle Visualisierung in die Irre geführt werden, aber die virtuelle Landmarke kann ihr räumliches Lernen unterstützen.

Um die Beziehung zwischen der Umgebung und der Aufmerksamkeit der Benutzer zu verstehen, analysierte die Autorin die Umgebungsmerkmale, die die Navigation der Menschen beeinflussen, und führte eine auf Eye-Tracking basierende Benutzerstudie durch, die unterschiedliche Blickverteilungen bei der Navigation in regelmäßigen und unregelmäßigen Straßennetzen ergab.

Die Publikationen, die im Rahmen dieser Arbeit entstanden sind, befassen sich mit Fragen des räumlichen Lernens bei der MR-basierten Navigation aus der Perspektive der Wahrnehmung des normalen Nutzers, der Schnittstellengestaltung und des Einflusses der Umgebung. Der technologische Einfluss auf das räumliche Lernen während der Navigation muss noch untersucht werden.

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List of Abbreviations

Abbreviation	Description
AR	Augmented Reality
BIM	Building Information Modeling
EEG	Electroencephalography
fNIR	functional Near Infrared Spectroscopy
FOV	Field of View
GNSS	Global Navigation Satellite System
HHD	Hand-Held Display
HMD	Head-Mounted Display
HUD	Head-Up Display
IPS	Indoor Positioning System
LBS	Location-Based Service
MR	MIXED REALITY
SDK	Software Development Kit
SLAM	Simultaneous Localization and Mapping
SOD	Sense of direction
VR	Virtual Reality
WPS	Wi-Fi Based Positioning System
XR	Extended Reatlity

1 INTRODUCTION

1.1 SIGNIFICANCE AND IMPORTANCE OF THE RESEARCH

Modern life is highly mobile. Navigation assistance plays an important role and has matured during the last decades. Outdoor navigation booms first due to the application of GNSS (global navigation satellite system), while indoor navigation is limited as it is difficult to get stable GNSS within the walls. People are used to relying on outdoor navigation applications in driving and walking, for business trips and vacations and look forward to indoor navigation assistance. Recently, two trends have been observable in the field of navigation, 1) navigation (both indoor and outdoor) should be not only functional but also user-friendly, for example, meeting users' personal needs and preserving their spatial learning ability, and 2) indoor navigation has become feasible, thanks to the development of indoor positioning technologies.

The long-term use and reliance on outdoor navigation applications have raised concerns from researchers (Gramann, Hoepner, and Karrer-Gauss 2017; Cock et al. 2019), police (BBC News 2020), and the public (McCullough and Collins 2019), mainly due to the unawareness of the environment and a loss of spatial ability of users. With navigation aids, users act less actively and are less willing to learn about the environment. In other words, users usually follow the navigation instructions passively. Yet, there is no guarantee that navigation aids are always available, and memory of the environment is essential for people's daily life. This **spatial learning** capability also contributes to performance in STEM domains (science, technology, engineering, and mathematics, Wai, Lubinski, and Benbow 2009), lifelong learning (La García de Vega 2019), and healthy aging (Fernandez-Baizan et al. 2019). Researchers and educators are responsible for exploring possible methods of motivating people to learn and avoiding overloading people's minds with spatial learning.

Modern people spend most time indoors (Klepeis et al. 2001), especially as the current coverage of "**indoor**" extends from daily buildings (such as universities, hospitals, or hotels) to underground, in the air, and to the deep sea. Despite the high amount of indoor time, people still get lost more likely indoors than outdoors (Bauer, Müller, and Ludwig 2016). Many factors influence indoor navigation, including the spatial structure of the building, the cognitive maps constructed during people's navigation, and the people's individual strategies and spatial ability (Carlson et al. 2010). Nowadays, indoor navigation aids can help overcome difficulties in the wayfinding process with the new indoor positioning techniques.

Mixed reality (MR) technology attracts much attention among the various technologies supporting indoor navigation. MR augments the physical world by displaying virtual elements and introducing additional information. MR-based navigation can be used on hand-held devices (HHD, e.g., navigation applications on smartphones, Figure 1-1(a)), head-mounted devices (HMD, e.g., Google Glass and Microsoft HoloLens, Figure 1-1(b)), and head-up displays (HUD, for cars, Figure 1-1(c)). Commercial navigation assistances on HHD and HUD are currently available. Navigation on HMD is rare as HMD itself is mainly used by specialists. However, with the vision of the "metaverse," there is a consensus that HMD MR has a high potential to help improve the quality of our daily life.

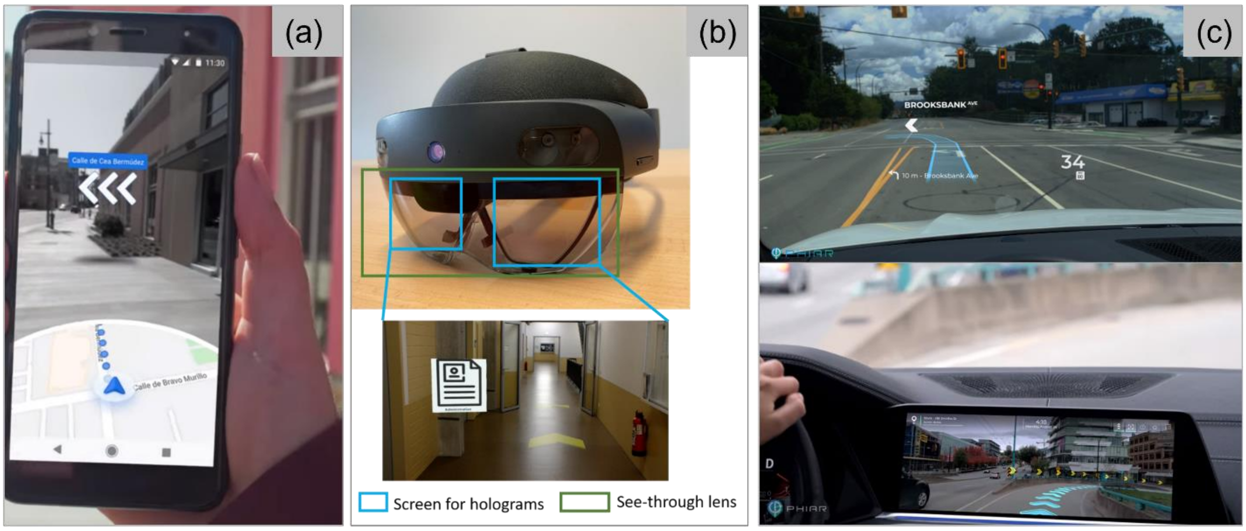

Figure 1-1 MR devices. (a) HHD (Google Maps Live View on a smartphone), (b) HMD (Microsoft HoloLens 1), (c) HUD (Screenshots of Phiar[1]).

[1] Phiar at CES 2022 – YouTube. 2022. https://www.youtube.com/watch?v=vg5Nz-dVwcE. Accessed 01/19/2022.

MR technology is applied in navigation, which is a process influenced by the environment and performed by people. Therefore, researchers contribute to MR-based navigation from diverse perspectives, as shown in Figure 1-2.

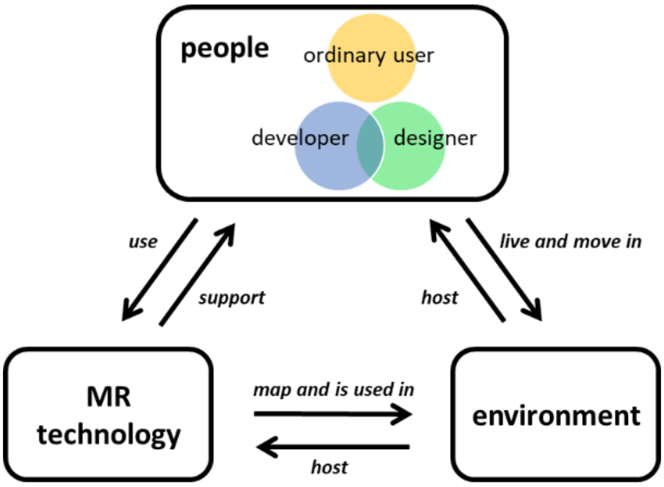

Figure 1-2 Research about using MR technology in navigation.

People live and move in the *environment,* and they develop, design, and use navigation applications based on *MR technology*.

Ordinary user – People who use or need to use the MR-based navigation applications in their daily life to move from a starting point to a destination.

Developer – People who realize the basic functionalities of MR-based navigation applications, e.g., path generation.

Designer – People who design the interface of MR-based navigation applications, e.g., visualization of direction instructions.

MR technology refers to the technical foundations, e.g., the device, of MR technology. Typical research in this field focuses on performance, such as computing and the sensory power of MR hardware. MR technology supports *people*'s navigation by mapping and augmenting the *environment*.

Environment is the space in which *people* move and use *MR technology*. Many environmental factors influence people's behavior and cognition, and the performance of MR devices.

With MR-based navigation, the loss of spatial learning might be even worse than with other navigation aids. Many studies have shown that MR users are intuitively attracted to the virtual elements and tend to ignore the physical world (Krupenia and Sanderson 2006; Gardony et al. 2013; McKendrick et al. 2016). Active exploration and decision-making are proven in the lab helpful for spatial awareness and spatial learning (Farrell et al. 2003; Ohm et al. 2014). However, it requires more mental effort, and might discourage ordinary users from using such applications – few users choose effortful tasks in daily activities. Fortunately, our brain learns more than we believe, even without us knowing. Research confirms that incidental spatial learning is possible, and it is the main difference between people with a good sense of direction (SOD) and those without (Burte and Montello 2017).

In this thesis, we try to tackle the dilemma of learning during navigation and the usability of MR-based navigation. More specifically, this thesis focuses on incidental spatial learning during MR-based indoor navigation by interface design.

1.2 RESEARCH CHALLENGES, QUESTIONS, AND TASKS

The primary aim of this thesis is to preserve and improve spatial learning during MR-based navigation. It involves research challenges in three aspects: 1) MR technology is quickly evolving, imposing an urgent need on user studies; 2) ordinary users of navigation assistance tend to ignore learning opportunities while moving, and incidental spatial learning is to be explored; 3) the environmental characteristics may influence people's navigation. Besides, current MR devices' limitations can cause spatial learning difficulties. Further technological progress may help overcome these limitations, which goes beyond the scope of this thesis.

Therefore, we focus on the following research questions:

RQ1 - How can we construct a minimal viable MR-based navigation application dedicated to studying user behavior?

RQ2 - How far can proper visualizations help preserve or even improve incidental spatial learning during MR-based navigation?

RQ3 - How is the users' attention influenced by environmental characteristics?

The research questions are answered by realizing the following research objectives through their corresponding tasks.

Objective 1 is to find the proper approaches to building an MR-based navigation application that can satisfy research requirements. This objective is achieved by two research tasks:

- **T1-device** Reviewing the available MR devices and the requirements and influence factors for user studies.
- **T2-approach** Summarizing the approaches to building an MR-based navigation application and their application scenarios.

Objective 2 is to understand how users' spatial memory is influenced by the interface and to visualize the navigation instructions in a spatial learning-friendly way. This objective is approached from both perspectives of the ordinary user and the designer:

- **T3-misleading** Examining whether ordinary users confuse the virtual and physical world during MR-based navigation and whether their incidental spatial learning ability is influenced by the instruction visualization.
- **T4-landmark** Exploring the possibility of using virtual landmarks to assist incidental spatial learning.
- **T5-users** Collecting ordinary users' opinions about MR-based navigation interface and improving navigation interface design for incidental spatial learning.

Objective 3 is to understand the environmental characteristics' influence on the users' attention. This objective is divided into two sequential tasks:

- **T6-environment** Identifying environmental characteristics that strongly influence people's spatial behavior or spatial ability.
- **T7-attention** Analyzing users' attention distribution for the similarities and differences while navigating different environments.

1.3 THESIS STRUCTURE

This is a *cumulative* thesis comprising four published peer-reviewed journal papers, and 1 additional contribution (journal paper in submission) in the Appendices.

Chapter 2 covers the necessary basics and state of the art for navigation and MR technology, the theory, and recent updates on how spatial learning happens and why it is essential. **T1-device** and **T6-environment** are achieved in this chapter.

Chapter 3 summarizes the key findings in four journal publications and one additional contribution and their relationships and discusses the contributions and remaining challenges. The full papers are attached as **Appendices**. The approaches to building MR indoor navigation for user studies are summarized and compared (App.A), and ordinary users' perception using HMD MR is explored (App.B). The effect of virtual semantic and structural landmarks is examined (App.C and App.D, respectively), and the need for adaptive design in MR navigation is emphasized (App.D). The structure of the environmental influence on visual attention is discussed (App.E). The findings in the five pieces of work are summarized, and the limitations are discussed. **T2-approach, T3-misleading, T4-landmark, T5-users,** and **T7-attention** are accomplished in this chapter.

Chapter 4 summarizes the contributions, concludes this thesis, and provides an outlook for future work.

2 Foundation and State of the Art

This chapter summarizes the foundations and state-of-the-art developments of indoor navigation, MR-based navigation, spatial learning, and memory anchors from practical and theoretical perspectives. We first compare indoor and outdoor navigation and propose applying MR in indoor navigation in Section 2.1. Then we introduce the development and implementation of MR in navigation, the cognitive issues coming along, and their impact on spatial learning in Section 2.2. The necessities, difficulties, and opportunities for preserving spatial learning are then summarized in Section 2.3. As an important method of spatial learning, memory anchors are introduced in Section 2.4. Two research tasks, **T1-device** and **T6-environment,** are handled in this chapter.

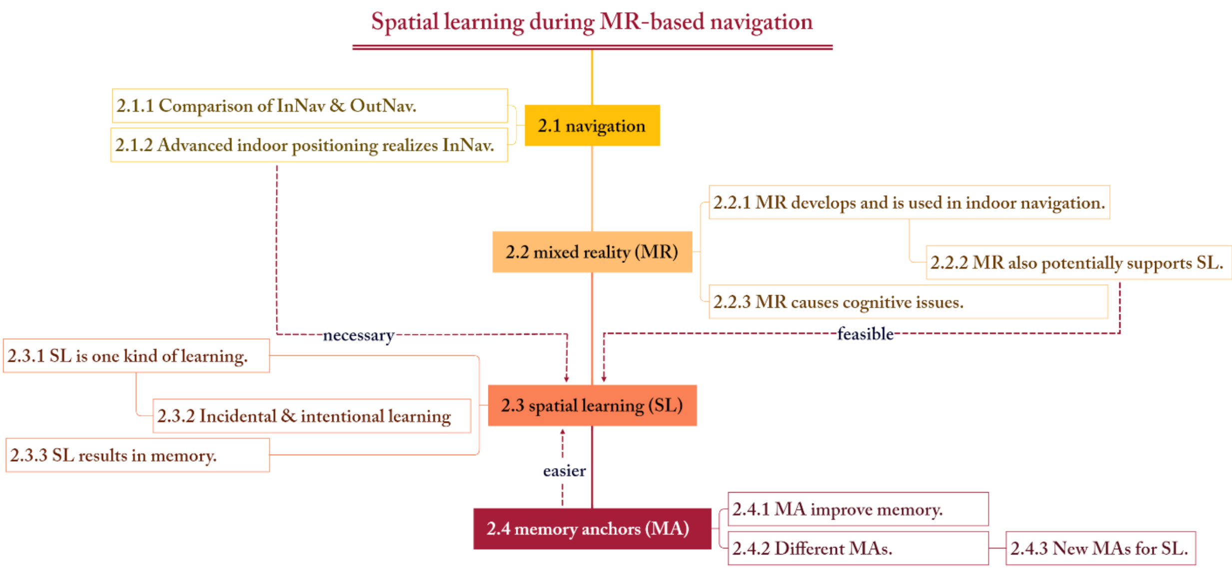

Figure 2-1 Structure of Chapter 2.

2.1 Navigation

Navigation is the process of planning the path and moving to the destination (Montello 2005). In path planning, people examine the environment and make decisions in mind. During moving, people explore the environment, acquire first-hand knowledge, and update their understanding of the environment. In general, we acquire spatial knowledge through navigation. This process is called **spatial learning**, which can happen intentionally or incidentally (see Section 2.3). In this section, indoor and outdoor navigation are compared along with an overview of the state of the art of indoor navigation.

2.1.1 Indoor and outdoor navigation

We navigate indoor, outdoor, and between indoor and outdoor. The foundations of navigation in all these cases are similar. We need to know the destination, move, orient and reorient ourselves, compare the actual position with the expected route in the mental map or physical maps, determine the next steps at decision points and repeat the process till the destination is reached. Navigation is a daily and yet complex activity. Many outdoor navigation assistances are available, and the navigation assistances for indoor and the transition between indoor and outdoor (Zeng et al. 2018) are being developed.

Research about navigation assistance can focus either on path generation or the moving process. The former aims to improve the positioning accuracy (Ostroumov and Kuzmenko 2016; Hübner et al. 2020) or generate better paths, e.g., by providing more context-based options (Duckham and Kulik 2003; Nandini and Seeja 2019; Truong-Allié et al. 2021). The latter includes mostly the interaction between users and the device and reveals that the usability of navigation assistance can be improved by providing intuitive interaction methods (Liao et al. 2019) or interfaces (Caduff and Timpf 2008; Duckham, Winter, and Robinson 2010). However, with the intensive use of convenient navigation assistance, the capacity of spatial learning may decline. Research emerges to study how to preserve spatial learning during the use of navigation assistance, either through explicit and active decision making (Wen et al. 2014; Brügger, Richter, and Fabrikant 2019) or through implicit and passive learning (Wunderlich and Gramann 2021; Liu, Singh, and Lin 2022). A unique research area about indoor navigation is positioning, which usually relies on GNSS for outdoor navigation.

Indoor referred to the "within-door" spaces when the term first emerged in the 18th century[2]. Efforts to distinguish indoor and outdoor have been made since the 2000s, as it would influence the development of other work, e.g., the Indoor Geography Markup Language (IndoorGML) (Chen and Clarke 2020). Chen and Clarke (2020) found in their review that most researchers regard spaces with full enclosure created by physical constraints and a finite size as *indoor*, while the *outdoor* space is opposite with unboundedness. Besides, indoor space has a greater level of complexity. In this thesis, "**indoor**" refers to the area with a closed space and it is big enough that people need to move to see the whole picture. For example, the interior space within a car is not qualified as indoor, whereas the interior space of a cruise ship is.

Indoor navigation differs from outdoor navigation in 3 aspects: human, space, and technique (Table 2-1). Humans refer to different frameworks for their navigation. While people switch between egocentric and allocentric frameworks during outdoor navigation (Lokka and Çöltekin 2020), it is usually difficult to use allocentric framework or the NSWE (north, south, west, and east) reference indoor. Outdoor navigation is provided to pedestrians, cyclists, and vehicles, and current indoor navigation mainly focuses on services for pedestrians. Outdoor and indoor spaces also differ in many aspects, including the lighting condition, visible landmarks, visual cues, dimension, and complexity. The lighting condition varies diurnally outdoor and is relatively constant indoor. Both local and distant landmarks are visible in outdoor space, while the indoor visibility is shorter due to the walls and other objects and only local landmarks are visible (Yang and Worboys 2011). As a result, more visual cues are identifiable in outdoor space than indoor space. Besides, navigating outdoor is mostly a two-dimensional task, but three-dimensional information is important in indoor space, as most buildings have more than one floor. All these factors make indoor space more complex to navigate (Hughes et al. 2015; Anagnostopoulos et al. 2017). As for the techniques, outdoor navigation mostly relies on the GNSS, while various methods (e.g., WI-FI, and RFID) are proposed for indoor positioning (Section 2.1.2) and there is no unified approach yet.

[2] "The World's Fastest Dictionary | Vocabulary.com." https://www.vocabulary.com/dictionary/indoor. Accessed 05/26, 2022.

Table 2-1 Comparison between outdoor and indoor navigation.

Category	Factor	Outdoor Navigation	Indoor Navigation
Human	reference framework	egocentric and allocentric	egocentric
	users	pedestrians, cyclists, vehicles	pedestrians
Space	lighting condition	diurnal	constant
	visible landmarks	local and distant	local
	visual cues	rich	limited
	dimension	two dimensions	three dimensions
	complexity	low	high
Technique	positioning technique	GNSS	WI-FI, RFID, etc. (Section 2.1.2)
	unified	yes	no

As modern people, we currently spend most of our time indoors, whether at home or in other buildings (such as universities, hospitals, or hotels). The indoor environment is purely "artificial". It can be highly personalized and complex (Hughes et al. 2015), and not in alignment with visitors' expectations (anti-intuitive) (Aksoy, Aydin, and İskifoglu 2020). It varies among different buildings. These factors make indoor navigation difficult for people. Besides, developing indoor navigation applications is challenging, mainly because GNSS signals for indoor positioning can be blocked by the walls and become unstable. Nonetheless, indoor navigation assistance is in great need in various scenarios:

- **Scenario 1:** A new student comes to the university for the first week lectures. He/she has been shown the most important locations for the study, such as the mostly used lecture rooms, the professor's/lecturer's offices, the administration offices, and the library. He/she knows the administration office and hands in some files there. The waiting time is longer than he/she expected, and he/she has five 5 minutes to go to the lecture room. Even though he/she has been guided from the administration office to the lecture room once or twice, the university buildings are too many/large for him/her to remember. Besides, most people around are freshmen like him/herself. He/she finds it is hard to reach his/her destination in a short time.

- **Scenario 2:** A newly recruited junior doctor of a big hospital is about to finish a night shift and he/she is exhausted. Suddenly there is a severe car accident, and the victims are sent to the hospital. He/she needs to first deal with the emergency admission to the operating room, and then accompany the coming family members to the waiting room. He/she is not familiar with the complex and large hospital building yet, and the worried family members kept him/her distracted.

- **Scenario 3:** A firefighter is called on duty. He/she got the floor plan of the building on the way and tried to make the most sense of it. Once he/she arrives at the fire point, he/she must make decisions and act fast, enter the building, and rescue the people trapped repeatedly. The fire is getting bigger, and the situation is getting more emergent.

The scenarios above are just a few examples demonstrating the great necessity for indoor navigation assistance. Indoor navigation is needed for more applications and people, such as a museum visitor who might want to find a particular piece of exhibit again or facility managers who report damages.

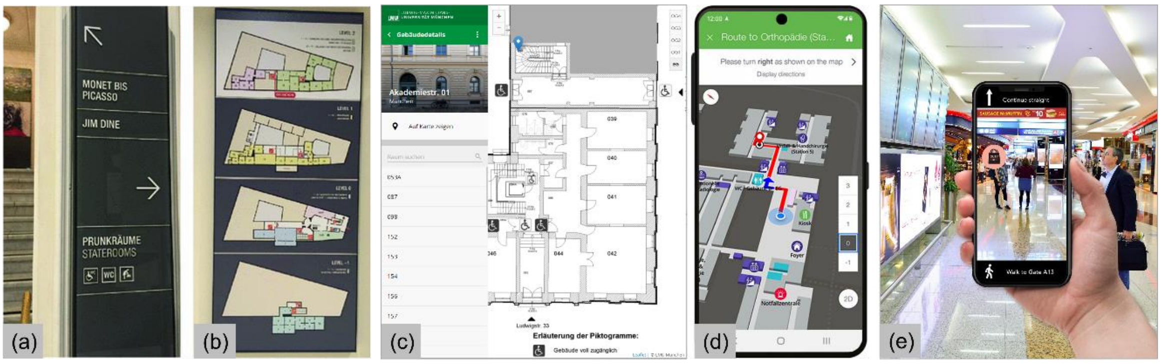

Figure 2-2 Indoor navigation services.

There have been different types of indoor navigation services. Big and complex buildings usually provide the signs (Figure 2-2(a), Wang, Huang, and Gartner 2018). Indoor floorplans are used as static signs (Figure 2-2(b), Wang, Huang, and Gartner 2018) or the base map of interactive (Figure 2-2(c), "LMU Raumfinder" 2022) and dynamic (Figure 2-2(d), infsoft 2022) navigation systems. A more attractive and "modern" method that is used by some airports for indoor navigation is MR-based navigation apps (Figure 2-2(e), Airport Suppliers 2020). Still, people get lost or even panic indoors in the stressed scenarios. Besides, no standards are available yet for an indoor positioning system (IPS). Instead, each installation and development of indoor navigation app is tailored to spatial dimensions, building materials, accuracy requirements, and budget constraints. The various available technical options for indoor navigation assistance may partly cause the difficulty of building a unified solution.

2.1.2 Available indoor navigation assistance

One of the main difficulties of developing indoor navigation applications is getting stable GNSS for indoor positioning. Emerging devices and technologies can be used for indoor positioning and navigation (Table 2-2). The data source, positioning type, and accuracy are summarized, and the difficulty of setting up, costs and usability are compared among those techniques.

Accuracy requirements of indoor navigation vary with the use scenario (El-Sheimy and Li 2021). For industry and construction, it should be centimeter/millimeter-level (Schneider 2010); for first responders, it should be decimeter-level in horizontal and floor-level in height (rantakokko 2010); for daily pedestrian applications, it should be meter-level in horizontal and floor-level in height (dodge 2013). As discussed in Section 2.1.1, GNSS, which is widely used for outdoor navigation with an accuracy about 5-10 m, is the least accurate for indoor positioning among the overviewed techniques. Apple's Indoor Positioning System (AIPS) uses the indoor WI-FI signal. It allows building owners to join Apple's indoor mapping project and create and update their own indoor maps. AIPS is also integrated with Apple's outdoor navigation service. Bluetooth beacons are used in places such as airports. The accuracy can be greatly improved by specific Bluetooth Ceiling Antennas to 10-50 cm, but it would require a wired network which is costly. Magnetic positioning uses the iron inside building for positioning and results in the accuracy of 1-2 m (Lee, Ahn, and Han 2018; Pointr 2022). Visual recognition, also called visual positioning system (VPS) is used in many MR devices (badmin 2020) with an accuracy in centimetres, which is sufficient for daily indoor navigation. A low-cost indoor positioning technique is based on visual markers/QR codes. The device recognizes the visual marker and locates itself. As the visual markers are constant, the positioning is stable with an accuracy of 5-15 centimeters. A detailed summary of the indoor positioning techniques is beyond the scope of this thesis and can be found in Kunhoth, J., (2020).

Table 2-2 Comparison of techniques for indoor positioning. Adapted from ViewAR GmbH (2020).

Name	Data	Type	Accuracy	Setup (1=easy, 5=hard)	Costs	Usability
GNSS	GNSS	2D	5-15 m	1	$	+
Apple's Indoor Positioning System	WI-FI	2D	4-8 m	3	$	++
Bluetooth Beacons	Bluetooth	2D	3-8 m	3	$	+++
Magnetic Positioning	iron inside building	2D	1–2 m	2	$	+
Visual Recognition	point cloud	3D/6DoF*	10-30 cm	4	$$	+
Marker/QR codes	visual marker	3D/6DoF	5-15 cm	1	$	++

*DoF: degree of freedom

Aside from the accuracy, the difficulty of setting up the devices is another concern in the usability assessment. Among all the techniques, visual recognition is most free, as it is based on point cloud and no extra devices are needed. MR mainly applies visual recognition and is always self-contained. Such convenience makes MR promising for indoor navigation.

While current commercial indoor navigation assistances are focusing on the functionality, the usability of indoor location-based service (LBS) is influenced by far more factors. For example, Open Geospatial Consortium (OGC) proposed IndoorGML as a standard for open data model and XML (extensible markup language) schema for indoor spatial information (IndoorGML OGC 2020). Hopefully, such standards could accelerate and improve the development of indoor navigation. Besides, the apps should be easy to use for the ordinary users. The second part of navigation, i.e., people moving to the destination, requires the proper communication between the machine and the people, especially for the indoor navigation (Puikkonen et al. 2009).

2.2 MIXED REALITY-BASED NAVIGATION

2.2.1 Mixed reality and its development

The term **mixed reality** became popular when HoloLens 1 was launched by Microsoft. Earlier than that, mixed reality was used to refer to the whole continuum from physical real environment (reality) to purely virtual environment (virtuality), including both *augmented virtuality* (AV, currently referred to as *virtual reality,* VR) and *augmented reality* (AR) (Figure 2-3, Milgram and Kishino 1994).

Currently, AR and MR both refer to the technology that displays virtual holograms and the real world simultaneously (Çöltekin et al. 2020b) and AR, MR and VR are all part of the *extended reality* (XR). In this thesis, "**mixed reality**" is used for both MR (as Microsoft refers to it) and AR. Current MR devices are mainly head-up displays (HUDs), hand-held (HHD, i.e., smartphones), and head-mounted devices (HMDs).

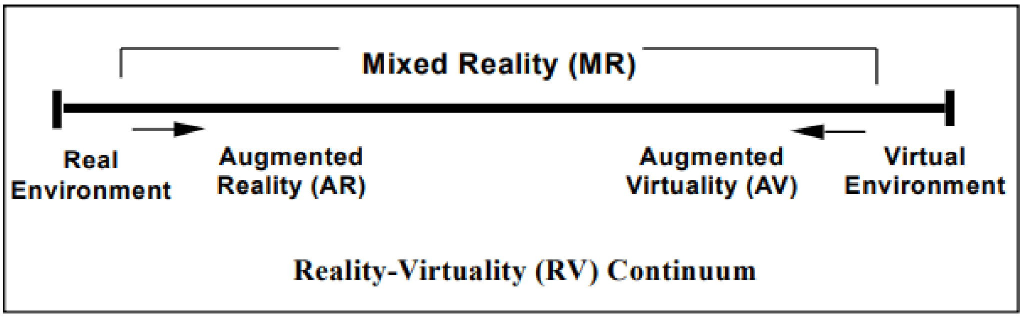

Figure 2-3 Reality-Virtuality (RV) Continuum (Milgram and Kishino 1994).

The idea of MR has already a rather long history. The American author L. Frank Baum first raises the idea of an electronic display that overlays data (in this case "people") onto real life in his story "The Master Key" in 1901, which is regarded as the first mention of AR/MR by Johnson (2012). The first HMD AR/MR dates to as early as 1968 (Sutherland 1968). The earliest MRs were used for spatial related tasks, such as Dan Reitan's overlaying geospatial maps with multiple weather radar images of the Earth to display weather broadcasts in 1981 (SysBunny 2021) and George and Morris (1989)'s work of an astronomical telescope-based "heads-up display" system. The most popular and successful MR application, Pokémon GO, is also heavily spatial related.

MR was used for the navigation purpose by Delgado et al. as early as 1999 (Delgado et al. 1999). As indoor navigation application, Shneiderman and Plaisant (2004, page 258- page 260) have already proposed to use MR for navigation in supermarkets or museums in 2004. Apart from its being intuitive and easy to use, MR is also unique in navigation as it displays the instructions directly on the physical world and has the potential to reduce attention split (see Section 2.2.3) between the device and the world and support spatial learning in the real world. In other words, MR-based navigation can potentially balance fun effects with practicality.

The research of MR-based navigation is inseparable from VR for a main reason that user studies in a large-scale geographical environment are time-consuming and it is hard to control influence factors, such like weather conditions, traffic and noise, and users usually have different prior knowledge about the study areas. To deal with these problems, VR has long been used as a substitute for a real-world environment to understand how people learn space in highly controlled lab conditions. VR allows conducting user studies of spatial learning experiments at different scales within a restricted physical space, such as a room, a building (Liang et al. 2019), or a city (König et al. 2019). In some cases, Morris water mazes (Ariel and Moffat 2018) are used to assure a totally controllable environment. VR also provides better protection against physical hazards and thus is widely applied in research on the increase or decrease of spatial ability (Farran et al. 2016). This is especially useful for user groups with limited abilities, such as the disabled, children, or the elderly.

Many sensors and devices are combined with MR or VR in research and practices (Table 2-3). **EEG** (electroencephalography) measures brain activity by sensing brain waves (Figure 2-4(a), Tauscher et al. 2019). EEG helmets are combined with MR/VR to test the task workload or emotions (e.g., mBrainTrain smartingPro[3]). However, EEG signal is sensitive to physical pressure and the weight of the XR helmets might cause distortions (Tauscher et al. 2019).

Eye tracker (Figure 2-4(b), Kapp et al. 2021) is used to get eye movement for research and interaction in desktop-based and mobile user studies, and now is already integrated in many MR/VR devices (e.g., Microsoft HoloLens 2[4]). The device and data are easy to access. The limitation is that eye gaze data is two-dimensional and usually lacks depth information.

fNIR (functional near infrared spectroscopy, Figure 2-4(c), Seraglia et al. 2011) uses specific wavelengths of light to measure cerebral oxygenated and deoxygenated haemoglobin that are correlated with the blood-oxygen-level-dependent (BOLD) signal (Artinis[5], Cui et al., 2011; Sato et al., 2013). It is also an objective, portable and non-invasive method with low cost. But its depth penetration is limited, and the motion artifacts should be dealt with.

Other physiological measures, such as facial muscle activations, heart rate and skin impedance are also collected to measure emotions and behaviors. EmteqPRO[6] provides a heterogenous and multimodal solution example. But the weight and size of the device restrict its usage in mobile studies.

GNSS (Figure 2-4(d), Julier et al. 2001) is used to get the geographical location. It improves the positioning accuracy for outdoor studies but is difficult to access indoor.

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[3] mBrainTrain. 2021. https://mbraintrain.com/smarting-pro-32/. Accessed 06/17/2022.

[4] Microsoft HoloLens 2. 2022. https://www.microsoft.com/en-us/hololens. Accessed 06/17/2022.

[5] Artinis Medical Systems | fNIRS and NIRS devices. 2022. https://www.artinis.com/nirs-devices. Accessed 06/17/2022.

[6] EmteqPRO by emteq labs. 2022. https://www.emteqlabs.com/emteqpro. Accessed 06/17/2022.

For the interaction, haptic gloves (Figure 2-4(e), Gebhardt et al. 2022), treadmills (Figure 2-4(f), Sloot, van der Krogt, and Harlaar 2014) and Kinect are combined to build more immersive and realistic virtual environments.

A common issue with the techniques listed above is that they are all unnatural and may raise self-awareness. It is not clear how far this issue interferes with users' performance and perception. The emotion and pressure biometrics might account for this.

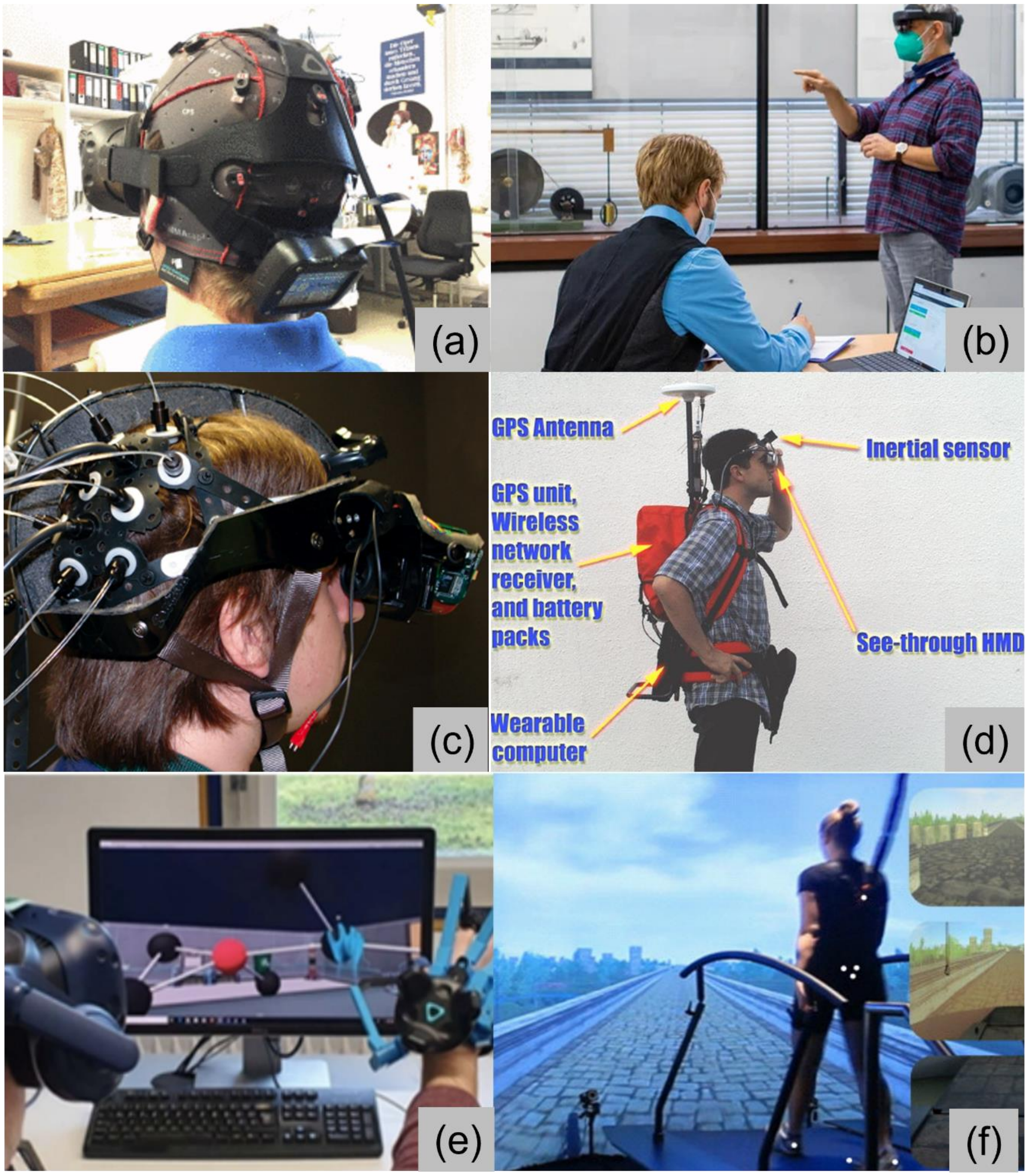

Figure 2-4 Sensors combined with MR/VR devices.

Table 2-3 Summary of the sensors combined with MR/VR. H: human, S: space, T: technique.

	sensor	data	aim	devices	advantages	limitations
H	EEG	brain waves	emotion/ workload	mBrainTrain smartingPro	high temporal resolution	signal distortion due to physical preasure and noise
	eye tracker	eye movement data	workload	Microsoft HoloLens 2	easy to access, integrated in many MR/VR devices	lack 3D information
	fNIR	brain activity	emotion/ workload	Artinis	portable, low cost, non-invasive; high temporal resolution	limited depth penetration; motion artifacts
	physiological measures	facial muscle activations, heart rate, skin impedance, etc.	emotion/ behavior	EmteqPRO	heterogenous, multimodal	weight, size
S	GNSS	location data	location	general GNSS devices	accurate position	unavailable indoor
T	haptic gloves	-	interaction	haptx	immersive multimoda	delay, extra devices to render virtual elements
	treadmill	-	interaction	Virtuix Omni	lab-friendly	constant environment

2.2.2 Implementation of MR-based navigation

MR-based navigation is already used in people's daily life. HUD MR is mainly for cars and other vehicles, as the augmented virtual elements are displayed either on an extra screen with real-time camera stream (Figure 2-5(a)) or the windshield directly (Figure 2-5(b)). The visualization of the camera streaming is easier, but the driver needs to switch their attention between the screen and the road. Overlaying holograms on windshields is more intuitive and the driver can focus on the road ahead in most situations. A main problem is that the display quality drops significantly in strong lighting conditions. Many cars have been equipped with HUD MR-based navigation in the form of MR dashboards such as MBUX AR in Benz and Phiar.

Figure 2-5 HUDs, (a) displayed on the windshield, (b) displayed on an extra screen with real-time camera stream. Screenshots of Phiar[1].

HHD MR is mostly used for pedestrian navigation. As the Google Maps Live View was first announced in I/O 2018[7], it attracted much attention and was supposed to help transition between indoor and outdoor navigation, for example, when the user exits a subway station and has no clue where to go (Li 2021). In the beginning, the interface was only with arrows and directions (Figure 2-6, left), and then the landmarks were also included to show points of interest and open/close

[7] Google Maps | Google I/O 2018. 2018. https://www.youtube.com/watch?v=1OMXn2GpBLc. Accessed 04/08/ 2022.

time, etc. (Figure 2-6, right). The HHD MR displays the augmented virtual holograms on the screen and attracts consumers. Most smartphones and tablets support MR. Some indoor MR navigation apps are already available for smartphones (such as XRGO[8] and INDOAR[9]). Like the camera streaming HUD, HHD MR also requires users to switch their attention between the screen and physical world (Stähli, Giannopoulos, and Raubal 2021). The high cognitive workload may lead the users to ignore the potential dangers. Therefore, Live View is only provided for pedestrian's mode in Google Maps and the users are suggested to put the device away once they understand the directions. Besides, it is not practical for multi-tasking users to always hold the smartphone in their hands.

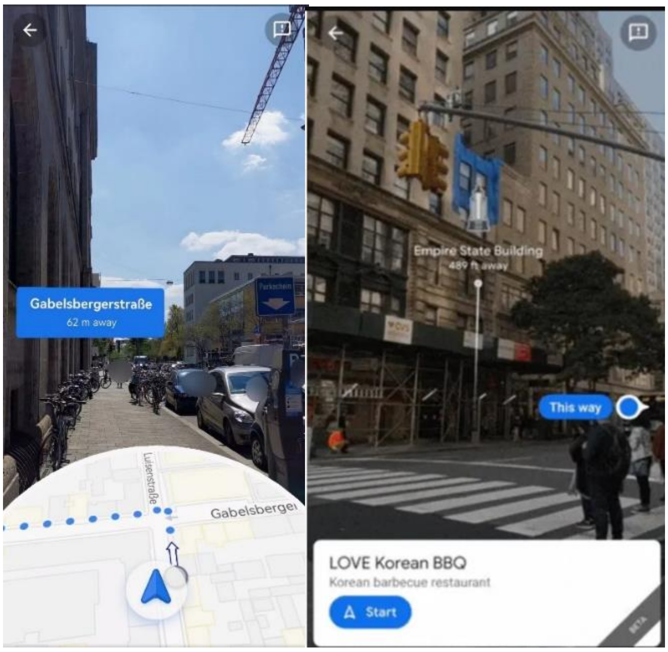

Figure 2-6 Google Maps "Live View" without landmarks (left) and with landmarks (right, Li 2020).

Currently, not many ordinary users possess an HMD MR device and therefore, the HMD MR-based navigation is not yet popular. Still, HMD MR is regarded highly potential for daily use, especially for navigation (Makimura et al. 2019; Thi Minh Tran and Parker 2020). Similar to the windshield HUD, HMD overlays the virtual objects directly on the real world, frees hands, and takes full advantage of the intuitive nature of MR. Many researchers are exploring the full potential

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[8] XRGO. 2020. Augmented Reality Indoor Navigation App for iOS or Android | XRGO. https://xrgo.io/en/product/ci-inplace/. Accessed 03/28/2022.

[9] INDOAR. 2022. INDOAR for Museums | Guided Tours & Immersive Experiences with augmented reality | ViewAR. https://museum.viewar.com/. Accessed 03/28/2022.

of MR-based navigation from the positioning (Hübner et al. 2020), interface design (Bolton, Burnett, and Large 2015; Chu, Wang, and Tseng 2017; Rehman and Cao 2017), and spatial learning (Huang, Schmidt, and Gartner 2012; Liu, Singh, and Lin 2022) perspectives. Some cognitive issues are revealed, and attention distribution is one of the most pressing research topics (Kishishita et al. 2014; Bolton, Burnett, and Large 2015; McKendrick et al. 2016).

2.2.3 Visual attention and spatial awareness

Visual augmentation is the most common method used by current MR. Visual attention distribution is widely studied by eye-tracking studies. Among the sensors and devices summarized in Section 2.2.1, eye tracker is also the least invasive (or the most natural). Eye-tracking technology is based on the eye-mind assumption, which claims that the eye movement reflects the cognition process (Kiefer et al. 2017). We process visual information during *fixations* and switch our attention between fixations by *saccades* (Ooms et al. 2012; Dong et al. 2018; Dong et al. 2020a). Eye movement data is ideal for the exploration related to visualization and is commonly used to explore how people process information (Liu, Dong, and Meng 2017; Carter and Luke 2020; Kapp et al. 2021).

Facing the daily information flood, we need to filter the noises and pay attention to the most relevant ones. In most cases we succeed in the selection task, but sometimes we are less attentive, miss the important hints, and then run into troubles. For example, one is in a hurry to catch a train, but he/she just cannot find the direction to the platform (even though the sign might be right in front of him/her).

A slight distraction can divide attention, decrease our perception of the surroundings, and hinder the main task. For example, phone usage during walking can interfere performance of tasks with just low cognitive demands (Hyman et al. 2010). The situation where we ignore the object in the plain sight and fail to notice the existence of an unexpected item is called **inattentional blindness** (Jensen et al. 2011), which is common in our daily life. We do not just ignore trivia objects but also safety-relevant visual stimuli (Murphy and Greene 2015), and real dangers come along (Simons 2000; Krupenia and Sanderson 2006; Kim, Nussbaum, and Gabbard 2016).

Although MR intends to augment the reality, inattentional blindness might be more common with MR. MR users see unnatural things and must switch their attention between holograms and the real world. Besides, some holograms are intentionally designed to attract users' attention and transfer the most critical information, and this may potentially interfere with the learning of other information.

In fact, increased inattentional blindness is found in MR. It is not surprising since people get easily distracted by the novel holograms and entertaining interactions in MR. Krupenia and Sanderson (2006) reported that the participants performed worse at detecting unexpected events wearing HMD MR. More recently, inattentional blindness has been confirmed in monitor-based MR (Dixon et al. 2014) and HUD MR (Wang et al. 2021). There is no clear conclusion on whether such inattentional blindness also exists in currently more advanced HMD MR.

The latent inattentional blindness in HMD MR might reduce user's spatial awareness. A common criticism of current HMD MR is the limited field of view (FOV), which increases inattentional blindness and attention tunnel may occur (Li et al. 2014; Syiem et al. 2021). Usually, it's only the screen for holograms that is with limited FOV, e.g., the screen for Microsoft HoloLens 2 is 43°×29° (Heaney 2019), but the rest is with lens and allows users to see the real world (Figure 2-7). However, users' attention tends to be attracted by holograms on the small screen and the peripheral vision for the physical world might decrease. Although researchers found extremely limited or no influence of FOV on pointing task in physical world (Barhorst-Cates, Rand, and Creem-Regehr 2016) or object placement in VR (Adhanom et al. 2021), it is not clear whether spatial learning of objects on sideways is affected.

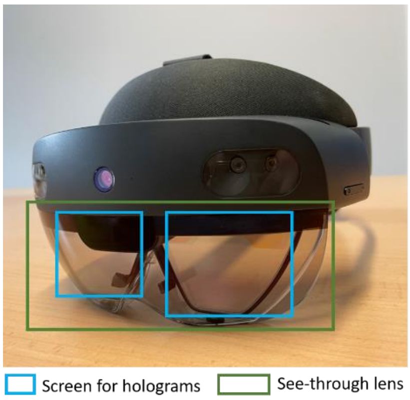

Figure 2-7 HMD MR example: Microsoft HoloLens 2. Blue: screen for holograms; green: see-through lens.

Users' visual attention and spatial awareness are critical to navigation success and enhanced spatial learning (Kapaj, Lanini-Maggi, and Fabrikant 2021). Previous research found the risk that the inattentional blindness can interfere with navigation and spatial learning and might impair users' spatial ability in a long run. With "traditional" navigation aids, such as human guide (as the freshman in **Scenario1**), or smartphone app, users are less attentive to the route and usually do not learn the space well (Stites, Matzen, and Gastelum 2020). The concentration on virtual visualization of HMD MR users may lead to a decreased perception of the real world (McKendrick et al. 2016) and a loss of essential information for safe navigation. Many researchers are trying to use as few and simple holograms as possible for the MR visualization to retain the users' spatial awareness (Bolton, Burnett, and Large 2015; McKendrick et al. 2016; Rehman and Cao 2017) and preserve the spatial ability in the long run.

Another concern about inattentional blindness is how the users handle the conflicts between the real physical world and the virtual visualization. Navigation aids need to keep users physiologically safe and not mislead them (Fang, Li, and Shaw 2015). But the virtual visualization in MR navigation can misalign with the physical world if the device malfunctions (e.g., the direction indicator might go through a transparent door) or is poorly, or even maliciously designed. With the possibly worse inattentional blindness, whether the virtual objects or environments could override the perception of real world and thus mislead users is not clear yet. This is like the misleading effects of map scale on geometry and feature selection (Monmonier 2005).

In MR, holograms can assist spatial learning by providing landmarks/anchors for spatial positions in large grids (Uddin, Gutwin, and Cockburn 2017). However, holograms should not be too many, nor occupy too much space, so that users are still allowed to see and learn the real world. Pointlike symbols are used for the visualization of structural information in the indoor space, in floorplans and evacuations maps. It's not clear if users' memory of the structural information resembles the visualization, that is to say, if the structural information is memorized as points.

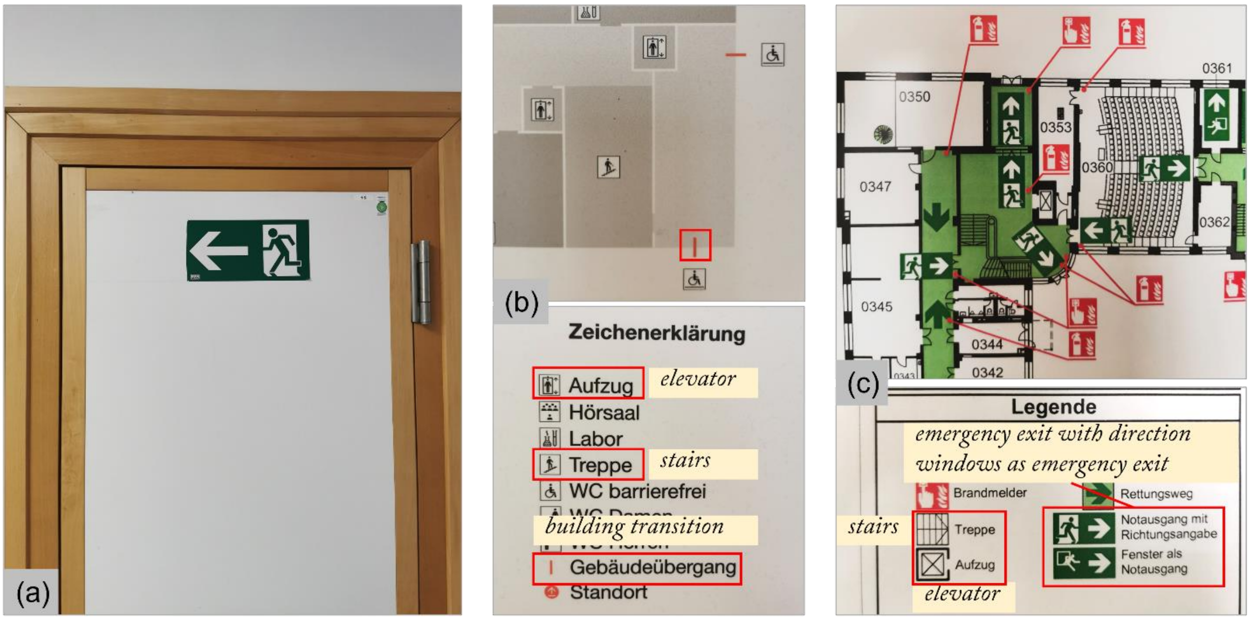

Figure 2-8 Pointlike symbols for structural information visualization. (a) on the door, (b) in floor plan, (c) in evacuation map.

2.3 Spatial learning

According to Cambridge Dictionary, the primary definition of **learn** is *to get knowledge or skill in a new subject or activity* ("learn" 2022). **Learning** is the process of acquiring knowledge and skills. To learn is to progressively form an internal model of the external world (Dehaene 2021).

Exploring the space and getting spatial memory is essential for animals to survive (Jeffery 2017; Dehaene 2021). Modern people living in safe built-up areas often ignore the space. However, there is no guaranteed safety and spatial learning is still necessary.

In outdoor space, people need to stay orientated, especially in case of machine failure (Brügger, Richter, and Fabrikant 2016) or machine misled by incorrect information. In indoor space, people need to develop a mental map for daily activities (e.g., as a student on the university campus or a junior doctor doing his/her job in the hospital) and evacuation in emergencies (e.g., a firefighter on duty). Machine and computation should augment, not replace people's thinking (Bach et al. 2017). Balancing spatial learning and navigation is necessary and possible (Brügger, Richter, and Fabrikant 2016).

2.3.1 Spatial knowledge and spatial learning

Spatial learning refers to the process by which an organism acquires a mental representation of its environment (Brodbeck 2012). Spatial navigation is one of the several major areas of knowledge (Dehaene 2021, p.140). Spatial knowledge reflects people's knowledge about the environment. It is categorized as landmark, route, and survey knowledge (Ishikawa and Montello 2006) and is essential in forming people's navigation behavior (Cock et al. 2019).

There is no solid theory about how spatial knowledge is acquired. According to Siegel and White (1975)'s *spatial cognitive microgenesis*, the internal representation of a new place is mainly landmark knowledge at the initial stage, then grows to route knowledge, which ultimately will be integrated as survey knowledge. This strictly stepwise learning theory was challenged by Ishikawa and Montello (2006). They conducted a user study with 10 weekly sessions and found that despite the individual differences in learning rate, the landmark, route, and survey knowledge are learned and developed at all stages, supporting Montello's *continuous framework* of spatial learning development.

While researchers try to form spatial learning theories and preserve spatial learning (Huang, Schmidt, and Gartner 2012; Ruginski et al. 2019), the easily accessible navigation aids nowadays can efficiently guide users to their destinations, this may inadvertently undermine ordinary users' spatial learning of the environment (McKinlay 2016; Gramann, Hoepner, and Karrer-Gauss 2017). The fact that an over-reliance on navigation assistance may damage spatial learning and spatial ability has raised public attention. Worse is that people's wayfinding ability might suffer in the long run (McKinlay 2016; Gramann, Hoepner, and Karrer-Gauss 2017). Besides the scientific evidence, police also encourage the public, especially the hiking people, not to neglect their own wayfinding ability (BBC News 2020). Even young people who quickly adopt new technologies express their concerns about GNSS compromising navigation skills (McCullough and Collins 2019). More and more people agree that the navigation assistance is supposed to help the spatial knowledge acquisition and spatial learning as well (van Asselen, Fritschy, and Postma 2006; Stankiewicz and Kalia 2007; Epstein 2020; Lu et al. 2021).

Still, spatial learning is not an easy task for navigation assistance design. Even with the intention or desire to learn, the ordinary users have multiple reasons not to learn the space in practice. Navigation is seldom the primary task. Modern people are busy and usually multi-task during moving, such as taking phone calls, chatting with friends, preparing for upcoming events, or searching for the points of interest (POIs). The multi-tasking and attention distraction degrades spatial learning and spatial ability to some extent.

The good news is that spatial learning also happens incidentally (Wenczel, Hepperle, and Stülpnagel 2017). Many studies show that users can perform secondary tasks while walking (McKendrick et al. 2016) and incidental spatial learning is possible (Wunderlich, Grieger, and Gramann 2022). However, if users are too concentrated on a main task, i.e., the navigation, the inattentional blindness may occur and incidental spatial learning is less likely.

2.3.2 Intentional and incidental learning

People actively attend to and learn many things in daily life. However, our brain processes and learns much more than we know. Everyday we are exposed to massive amounts of information and the brain implicitly filters the noise and learns something we might not be aware of. Learning happens both intentionally and incidentally.

Intentional learning is generally defined as learning that is motivated by intentions and is goal-directed. The term "intentional learning" was used by Bereiter and Scardamalia (1989) to "refer to cognitive processes that have learning as a goal rather than an incidental outcome" (p. 363). The learning process *per se* happens consciously with objective intention (Blumschein 2012). Attention and active engagement are proposed to be among the four pillars of learning by Dehaene (2021). That is true about the learning in class, which always include learning, processing, and reasoning as Dehaene was discussing education. For example, intentional learning results in better performance than incidental learning in a color-recalling task (Ahmed 2017).

Intentional learning is proved to be helpful for preserving spatial learning in labs. Active decision making is included in navigation process (Farrell et al. 2003; Wen et al. 2014; Brügger, Richter, and Fabrikant 2019). Some researchers also believe users can only learn spatial knowledge by actively exploring or remembering the environment according to the active encoding principle (Brügger et al. 2019) and try to involve the users in the decision-making process (Wen et al. 2014). The research also reveals that intentional learning requires time and mental efforts. This extra workload weakens the usability of intentional learning in commercial applications and daily life.

New knowledge and skills are also learnt unplanned and incidentally. The latent or **incidental learning** happens spontaneously and results in the by-product, incidental memory (Glisky 2011). Incidental learning is as promising as intentional learning. It is reasonable that intentional learning often leads to good memory. According to Craik and Tulving, it is not the intention to learn that was critical for later memory, but rather the type of processing engaged at the time of encoding

(Kelly 2012). Information that was processed meaningfully was well remembered whether there was an intention to remember. Another kind of learning without intention is implicit learning. The difference between incidental and implicit learning is that the knowledge acquired in incidental learning can be verbalized or communicated in other ways, while the latter cannot (Martini and Gaschler 2020). In other words, incidental learning does not damage the meaningfulness of the acquired knowledge. Therefore, improving people's incidental learning might be more promising and practical in navigation.

Since people usually do not have the intention to learn the space, exploring possible ways to enhance the meaning of the space is important for incidental spatial learning (Gramann, Hoepner, and Karrer-Gauss 2017). Learning intention almost showed no influence on spatial learning (Burte, Montello 2017). The incidental rather than intentional spatial learning distinguishes people with and without a good sense of direction (SOD). Incidental spatial learning can be improved, e.g., by modified navigation instructions (Gramann, Hoepner, and Karrer-Gauss 2017). van Asselen, Fritschy, and Postma (2006) explored the influence of intentional and incidental learning on spatial learning. They only found difference on map-drawing and navigation task, where the intentional group performed better. No difference was found on the landmark-recognition and landmark-ordering tasks. Besides, the learning intention influences the estimation of walking distance (the intentional group overestimated while the incidental group underestimated it). These results suggest that route knowledge acquisition is less effort-demanding than survey knowledge acquisition.

2.3.3 Memory

We get spatial knowledge through spatial learning, and the knowledge is stored in memory. Understanding how memory is developed and stored improves our understanding of spatial learning and how to improve it.

We have working memory to temporarily hold limited pieces of information in awareness while processing them (Borders 2020), short-term memory to encompass cognitive functions for the storage, maintenance, and mental manipulation of information that is no longer present in the sensory environment (Katus and Andersen 2015) and rely on long-term memory to recall the information after a delayed interval during which our attention is off the target item (Kramer and Stephens 2014). Sometimes working memory is regarded the same as short-term memory. However, they are not identical and revoke many discussions (Cowan 2008). In this thesis, working memory is regarded as part of short-term memory. Parts of short-term memory would be stored in long-term memory with rehearsal and the other parts would be forgotten (Figure 2-9).

Spatial memory is a combination of spatial working memory, short-term spatial memory, and long-term spatial memory. Spatial working memory and short-term spatial memory allow us to remember the object locations, relationships and help us explore and navigate a new space. The spatial memory we can retrieve and use in daily activities belongs to long-term spatial memory, more specifically, the explicit memory.

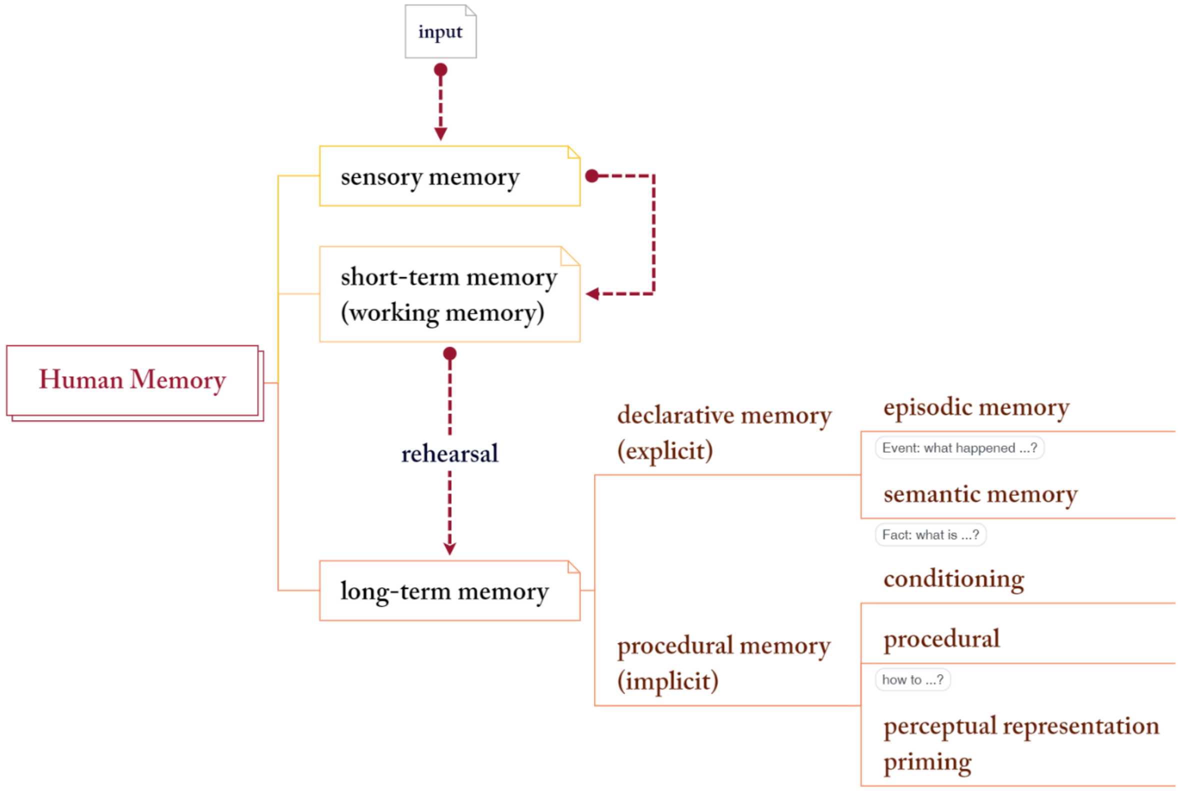

Figure 2-9 Memory structure and development.

Explicit memory is one of the two types of long-term memory and is also called declarative memory. It is the memory that can be expressed voluntarily, by language and other communication manners (Jawabri and Cascella 2022). Explicit memory can be semantic and episodic memory. Semantic memory is the memory about facts, e.g., what a bike is. Episodic memory is about the event (where, what, how something happened), or a process. It is the memory of experiences and specific events that occur during our lives, e.g., the memory of riding a bike on the first school day.

Implicit memory is mainly procedural memory, consisting of conditioning, procedural and priming memory. When people refer to implicit memory, we do not purposely try to remember it. An example of implicit memory is riding a bike.

Learning strategies are developed to improve our memory. Education can enhance learning (Dehaene 2021) and the educated person can learn twice the capacity as uneducated. In learning of general knowledge, **memory anchors** are proved to be helpful.

2.4 ANCHORS FOR LEARNING

The working memory capacity is limited (Cowan 2008) and people do not learn everything at the same time. We rather learn new information and integrate it to the knowledge that we already had. We could learn pieces by pieces or learn hierarchically. In both ways, we first acquire certain knowledge and form long-term memory, and the future new knowledge "grows" on it. There are certain methods that can prevent memory from flowing away, which is sometimes called **memory anchor**[10].

2.4.1 Definition of memory anchors

Memory anchor is not clearly, scientifically defined. However, this concept is ubiquitous in learning and memory. In Glossika's webpage, memory anchor is defined as a cue that helps memory recalling and it can be visual, audio or based on other senses[10]. A memory anchor is possibly a photo of friends laughing on a party, a song from schooldays, or a taste or scent of a special dish. It reminds people of the certain memory.

In education, tools or strategies are developed to improve learning (Dehaene 2021), among which **anchored instruction** and **anchor charts** are used for good teaching and learning in classes.

Anchored instruction (Figure 2-10, left) is a technology-centered learning approach and a form of situated learning (Lee 2002). Anchored instruction addresses the importance of context-based learning. The students are given a specific problem to solve and assigned realistic roles.

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[10] Glossika. 2017. "Memory Anchors." https://medium.com/@glossika/memory-anchors-7228030304f1. Accessed 06/05/2022.

During teaching/learning, activities are designed or tied around an adventure or story, which is the "anchor". Anchored instruction recalls the knowledge that students already have but may not recall for a long period. With the goal to solve a specific problem, such knowledge is used and rehearsed.

Anchor chart (Figure 2-10, right) is a tool created by the teacher and the students, and it documents the modelled steps, or thinking processes on large chart paper to anchor student's learning (Bacchioni and Kurstedt 2019). It provokes thinking in the classroom, visualizes the most important content and relevant strategies (Mulvahill 2020). By "anchoring" the learning, students may improve learning outcomes.

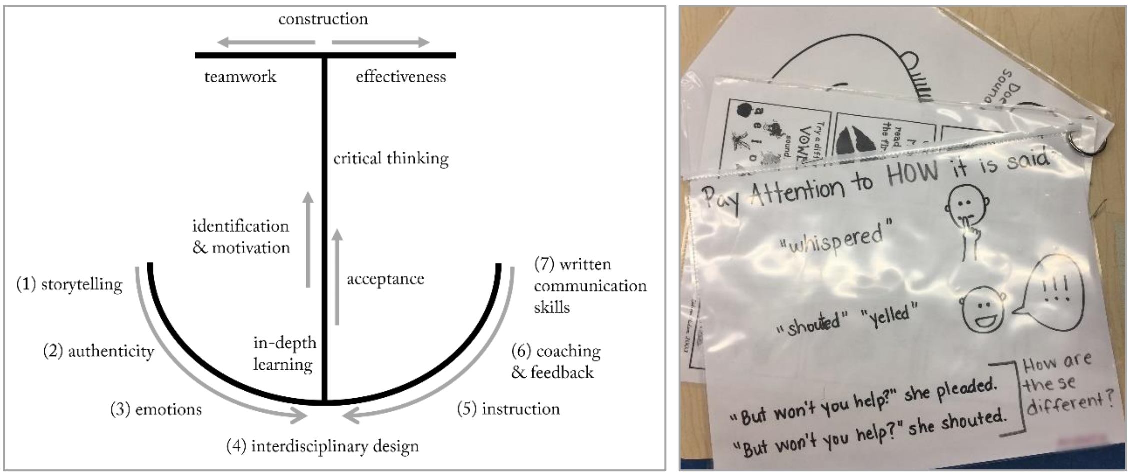


Figure 2-10 Anchored instruction (left, adapted from Wuttke-Hilke, Wagner, and Widmayer 2020) and anchor charts (right).

In research, anchor points have been proved to improve adults' learning of miniature artificial language (Valian and Coulson 1988), helping the participants understand the language structure and learn it quickly.

In this thesis, we define a **memory anchor** as the reference that can help people recall memory. Different from the definition above (Glossika[10]), a memory anchor can be a simple visual/audio cue, or an ingrained memory (including episodic memory).

2.4.2 Different memory anchors

Memory anchors are widely used to improve memorizing ability. As learning is influenced by different aspects, memory anchors are diverse. Three types of memory anchors are relevant for the thesis.

- **Mnemonics.** Mnemonics are traditional memory anchors and long used in learning and studying. They can be divided into nine categories (Heerema 2015). Such as using keyword mnemonics for language learning, using musical mnemonics to help teach (e.g., the "ABC" song). Method of loci is one of the most studied mnemonics. People acquiring this technique create and use their own Memory Palaces to remember information (McCabe 2015). Note that although loci are used as a mnemonic, no anchors are clearly defined for spatial memory yet. Chunking, as a mnemonic strategy, usually helps us remember verbal information, e.g., the phone number. Chunking the spatial knowledge is proposed to improve spatial learning but has not been proved yet (Liu and Zhan 2021).

- **Prior knowledge.** New knowledge is learned and integrated into previous knowledge. In spatial learning, people can learn the location of a new country based on the prior knowledge about the other countries, e.g., Liechtenstein is in Europe, located between Switzerland and Austria. In the meantime, new knowledge is generated by relating the prior knowledge: Switzerland and Austria are close to each other and might have shared borders.

- **Ingrained episodic memory.** Significant events are engraved in the brain and can be a reference for other memories. Emotional events are ingrained into memory stronger than neutral ones (Haas and Canli 2008). The problem of ingrained episodic memory is that it may be misled by other factors and results in distorted or fake memory. For example, people in the United States have strong episodic memory about the attack of September 11, 2011. However, their memories are inconsistent (Hirst et al. 2015).

Memory anchors are also promising in assisting spatial learning and improving spatial memory. According to the anchor-point theory of spatial cognition, people first learn the primary nodes or reference points and anchor distinct regions in cognitive space, and then the pieces are gradually brought together and integrated as a mental map (Couclelis et al. 1987). Memory anchors might help anchoring the distinct regions at the first stage. **Landmarks** are regarded as anchors during navigation (Bauer, Müller, and Ludwig 2016; Uddin, Gutwin, and Cockburn 2017).

2.4.3 Landmark as a spatial memory anchor

Landmarks are salient objects, and are categorized as visual, semantic, or structural landmarks (Sorrows and Hirtle 1999; Raubal and Winter 2002). These categories are widely accepted and considered in landmark salience evaluations (Lara, Antonio, and Peña 2018; Zhu et al. 2019; Wang et al. 2020). A good landmark should be permanent, visible, unique, easily identifiable and with a useful location (Bolton, Burnett, and Large 2015). Although there is no decisive theory about the learning sequence of the landmark, route, and survey knowledge (as discussed in Section 2.3.1), both theories, i.e., the *spatial cognitive microgenesis* and the *continuous framework*, agree that landmark knowledge develops at the very early stage of learning. This agreement suggests that learning of landmark is probably the easiest and thus more promising for incidental spatial learning.

Landmarks have been proved to be helpful in spatial learning. Based on the distinction between intentional and incidental learning (Section 2.3.2), approaches to improving spatial learning can be categorized into active decision making (Farrell et al. 2003; Wen et al. 2014; Brügger, Richter, and Fabrikant 2019) and incidental spatial learning (Gramann, Hoepner, and Karrer-Gauss 2017; Liu, Singh, and Lin 2022). For the latter, many researchers examined the feasibility of integrating landmarks in route description (Duckham, Winter, and Robinson 2010; Krukar, Anacta, and Schwering 2020). Landmarks are proved to be useful and intuitive in navigation (Bauer, Ullmann, and Ludwig 2015; Bolton, Burnett, and Large 2015; Wenczel, Hepperle, and Stülpnagel 2017; Çöltekin et al. 2020a; Dong et al. 2020b) and preferred by users (Ohm, Ludwig, and Gerstmeier 2015).

Although there is still debate on the significance of different landmarks (e.g., at-turn and straight-by landmarks, Fellner, Huang, and Gartner 2017; Wenczel, Hepperle, and Stülpnagel 2017), landmarks are doubtless "anchor points" that support users' self-localization (Bauer, Müller, and Ludwig 2016). Including landmarks in the route instructions improves incidental spatial learning in real walking scenarios (Wunderlich and Gramann 2019) and within the driving simulator (Krukar, Anacta, and Schwering 2020). Li et al. (2014) found that visualizing distant landmarks supports users with low SOD orientating. Credé et al. (2020) confirmed that globally visible landmarks help improve survey knowledge acquisition. Landmark learning is also a common task for the evaluation of spatial learning (van Wermeskerken et al. 2016; Hedge, Weaver, and Schnall 2017).

However, integrating landmarks is not easy for indoor navigation either. Public buildings can be complex (Wang et al. 2019) and lack visually salient landmarks that can be used for efficient navigation, which is one of the possible causes of getting lost indoor (Dubey et al. 2019). Indoor environments can be highly identical in some public buildings, such as the universities and hospitals (or other indoor environments, e.g., in ships). People get easily lost when they try to find their way in such indoor spaces, as they tend to search for visual instead of semantic landmarks in complex decision-making situations (Dong et al. 2020b). Rooms with particular functions in such buildings, e.g., university administration offices and hospital conference rooms, might be relevant to most people and semantically salient. Structural landmarks, e.g., the open space and the stairs, also have the potential to assist indoor navigation (Vanhaeren et al. 2020). However, identifying such landmarks is difficult for people, as they are either not visually salient or cannot be seen from a single viewpoint. This problem of the lacking landmarks may be relieved with the help of MR. For example, holograms can be used as *virtual landmarks* to highlight such visually not-salient landmarks.

Still, there is no guarantee that the additional virtual information and the current MR technology can assist landmark learning. Multimedia learning, which is common with MR, requires people to split their attention among multi-sourced information and integrate it mentally. It calls for more working memory and therefore may impair learning (Mayer and Moreno 1998; Ayres and Sweller 2005). This *split attention effect* is not only between vision and auditory (Kalyuga, Chandler, and Sweller 2004), but also happens within vision, e.g., between pictorial and textual information (Mayer and Moreno 1998). Virtual landmarks are also visual stimuli and are expected to be spontaneously integrated with the real world by people. However, it is unclear yet how the ordinary users perceive or switch their attention between them in actual usage.

With the current MR devices, the FOV is usually quite limited, and ordinary users tend to concentrate on the novel technology and ignore the real world (Section 2.2.3). Besides, when overloaded by the main task, people's "subjective" visual field is narrowed (Kishishita et al. 2014) and the secondary task (in this case, landmark learning) is impaired. In fact, recent preliminary evidence from Dong et al. (2021) is that although users' interaction intensity with 2D maps and hand-held MR navigation shows no significant difference, the users navigating with MR navigation aid remember the route significantly worse.

Given the contradictory influence of virtually visual saliency versus split attention, extra workload and limited FOV, the question of whether virtual landmarks can assist incidental spatial learning in MR-based indoor navigation remains open and challenging.

3 Summary of the Work

Three research objectives are proposed in Chapter 1, i.e., (1) finding the proper approaches to building an MR-based navigation application that can satisfy research requirements, (2) understanding how users' spatial memory is influenced by the interface and visualizing the navigation instructions in a spatial learning-friendly way, and (3) understanding the environmental characteristics' influence on the users' attention. Seven research tasks are identified to achieve these objectives.

Four journal publications (App. A-C, E) and one additional contribution (App.D) generated in exploring these research objectives are summarized in this chapter. The relations between the objectives and the tasks and the subchapters are illustrated in Figure 3-1. The methodological paper A (Section 3.1, App.A) focuses on the **development** of MR-based navigation applications for user studies and serves as the foundation for subsequent user studies. Paper B (Section 3.2, App.B) examines the misleading effect of MR-based navigation and spatial learning for **ordinary users**. Paper C (Section 3.3, App.C) addresses the **design** of virtual semantic landmarks and its influence on sptail learning. Paper D (Section 3.4, App.D) furthers the study by **designing** virtual structural landmarks and involving **ordinary users** in interface design. The influence of **environmental** structure on visual attention distribution is studied with the example of road pattern in Paper E (Section 3.5, App.E). The findings and limitations of these studies are discussed in Section 3.6.

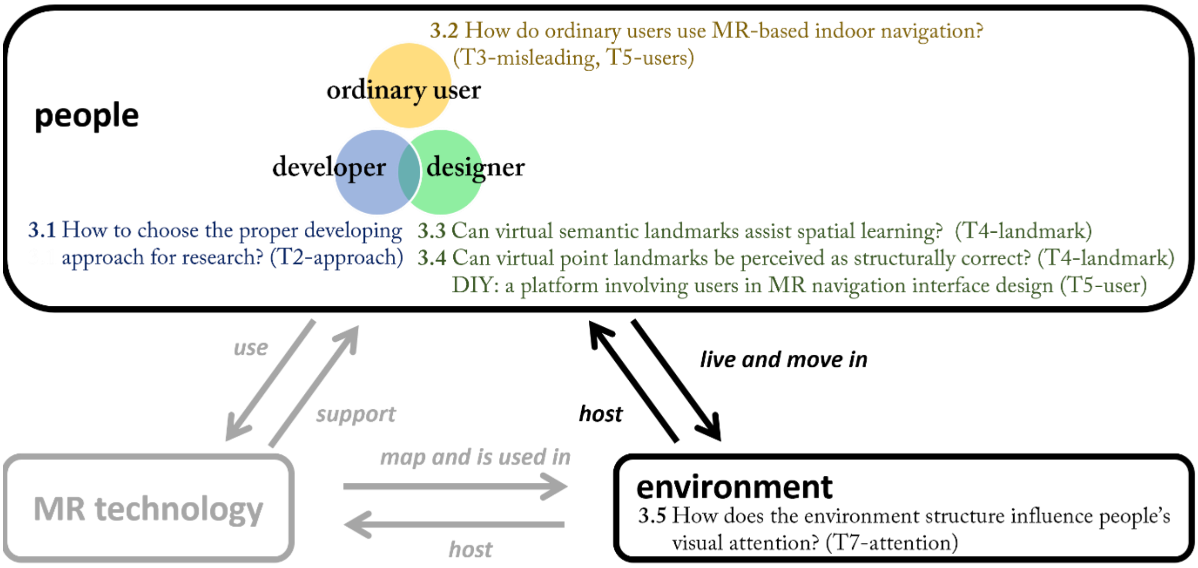
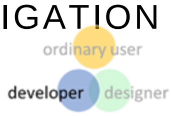


Figure 3-1 Structure of Chapter 3. Organization of the research items in this thesis.

3.1 APPROACHES FOR BUILDING MR-BASED NAVIGATION FOR USER STUDIES



MR, as a rapidly evolving technology, is being increasingly applied for navigation. Current non-MR navigation products usually provide navigation apps and SDKs (software development kits) that are ready to use, and researchers can quickly develop the navigation application. However, developing MR-based navigation is more challenging for research purposes.

Researchers are usually themselves **developers** for their study, i.e., they need to develop MR-based navigation projects by themselves. The HMD MR technology has become popular for less than one decade, findings of first person-view navigation are rarely reported, and few tools or guidelines for building MR-based navigation are available. Building a fully functional MR-based navigation application is costly and time-consuming; therefore, not worthwhile for research purposes. This work (APP.A) summarizes the approaches to building MR-based navigation for research purposes, completes **T2-approach,** and provides guidelines for developing MR-based navigation in the subsequent user studies (Section 3.2-3.4, App.B - App.D).

This work first reviews MR technology, devices, and the design of MR-based indoor navigation systems for user studies. Generally speaking, the HUD MR is used in cars, and HHD (mainly smartphones) and HMD MR are used for pedestrian navigation. HHD MR can be used both outdoor and indoor. HMD MR performs better for indoor navigation, as inconsistent lighting conditions make the display unstable for outdoor navigation.

A theoretical framework of spatial mapping, spatial localization, path generation, and instruction visualization is proposed (Figure 3-2). Some critical factors to be considered in the user study design process are summarized, e.g., the accessibility and safety of the study area. The framework also provides a reference for researchers to identify other possible factors.

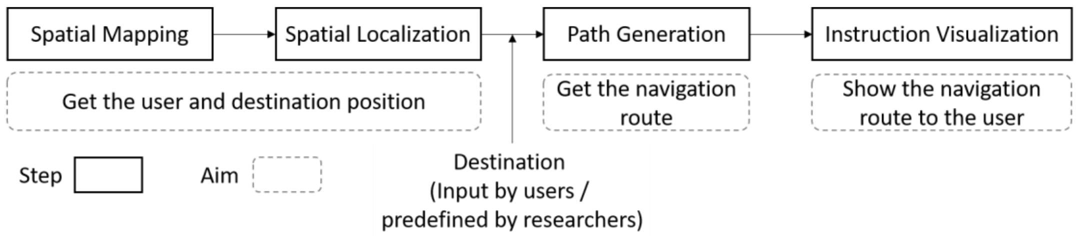


Figure 3-2 A general framework for designing MR-based navigation system.

Four approaches to constructing an MR-based indoor navigation system are introduced and compared in terms of their requirements and performances. The approaches are categorized based on two factors: (1) spatial anchor, i.e., whether the spatial anchor is stored locally or on the cloud, and (2) path generation, i.e., whether the path is predefined or generated in real-time. The comparison is summarized in Table 3-1.

Table 3-1 Comparison of four approaches. L: local anchor, C: cloud anchor; P: predefined path, G: generated path; BIM: building information modeling.

Anchor	Path	Require internet	Require BIM	Stable anchor position	Flexible path	Suitable for big study area	Required coding abilit
L	**P**	No	No	No	No	No	Low
L	**G**	No	Preferred	No	Yes	No	High
C	**P**	Yes	No	Yes	No	No	Medium low
C	**G**	Yes, strongly	No	Yes	Yes	Yes	High

The gained insight about the requirements and suitability of different developing approaches for MR in this overview helps select optimal design approaches for MR-based indoor navigation in the following case studies and is also generally helpful for all researchers who share the interests in MR-based indoor navigation research.

3.2 MISLEADING EFFECT AND SPATIAL LEARNING IN MR-BASED NAVIGATION

Much research has been conducted to investigate the navigation experience in MR. Despite the amusement effect and great potential of MR navigation, safety concerns arise when users are too concentrated on the animation to notice real dangers. Much effort has devoted to address these concerns, for example, Google Maps suggests their users of hand-held MR-based navigation to turn off the device during walking. However, the first-person view and field of view (FOV)-limited navigation experience are novel for both the users and the researchers. How **ordinary users** react to HMD MR-based navigation, especially in terms of spatial learning, is not clear yet.

This study tackles **T3-misleading** and covers **T5-users** by investigating how visualization in MR navigation affects users' memory of the environment. More specifically, two related hypotheses are tested: 1) incorrect virtual information misleads users' perception of the physical environment and leads to wrong spatial memory; 2) aligned separate holograms as direction indicator are perceived as a continuous path without additional mental efforts and do not influence spatial learning.

A user interface in Microsoft HoloLens 2 was designed, and a user study was conducted. An artificial turn was included in the path displayed, and the directions indicator was designed as arrows with or without connecting lines (Figure 3-3). The user study consists of a walking session, pre- and post-walking questionnaires, sketch map drawing, and a semi-structured interview about the user interface design. A cloud spatial anchor and predefined path were used in this user study.

Forty ordinary users (22-49 years old, 17 females and 23 males, recruited with posters on the university campus and online) wore Microsoft HoloLens 2 to navigate toward an unknown destination during the walking session. They had limited experience with MR/VR when the study was conducted.

Figure 3-3 Incorrect visualization (the artificial turn) in both groups.

Preliminary confirmation of **T3-misleading** is found that users' spatial learning can be misled by incorrect information, even in a small study area. Still, this misleading effect can be compensated by considerate visualization, e.g., including lines instead of using only arrows as direction indicators. Arrows with or without lines as two visualization alternatives also influenced the user's spatial learning and evaluation of the designed elements. Besides, the study covers **T5-users** and shows that ordinary users' preferences for navigation interfaces are diverse, and an adaptable interface should be provided. The results contribute to the design of head-mounted MR-based navigation interfaces and the application of MR in navigation in general. Moreover, the results prove that the proposed **development** approaches in Section 3.1 are feasible, as no participant complained about the functionalities of the navigation application.

3.3 VISUALIZING VIRTUAL SEMANTIC LANDMARKS FOR SPATIAL LEARNING

Landmarks are essential and widely used in human navigation. However, many indoor environments lack visually salient landmarks, leading to difficulties navigating and learning complex, similar-looking indoor environments. It depends on the **designers** of the navigation interface to visualize the hidden landmarks. **T4-landmark** is partly answered in this study.

In this study, we designed and implemented virtual semantic landmarks in MR-based indoor navigation and conducted a user study in a university corridor, which lacks visual landmarks (Figure 3-4, left), to explore whether such landmarks can assist incidental spatial learning during navigation. We employed Microsoft HoloLens 1 and designed iconic holograms to show the semantic landmarks (Figure 3-4, right). A local spatial anchor and predefined path were used in this user study. The participants of the user study provided their demographic information, and they were asked to wear the HoloLens to reach the destination following the route displayed. The video-taking function of HoloLens was used to record what the participants saw during the walking. Sketch mapping and landmark locating tasks were performed to assess the results of the spatial learning, and semi-structured interviews were conducted to collect ordinary users' advice on improving the MR-based navigation interface.

Figure 3-4 Study area (left) and the designed navigation interface (right).

Twenty-eight participants (21 - 48 years old, 12 females and 26 males, recruited via online or on-site ads) took part in the user study. They were informed that questions about the path would be asked before walking. Yet, they concentrated on the virtual instructions and forgot to "memorize." This confirms that intentional spatial learning during navigation is difficult.

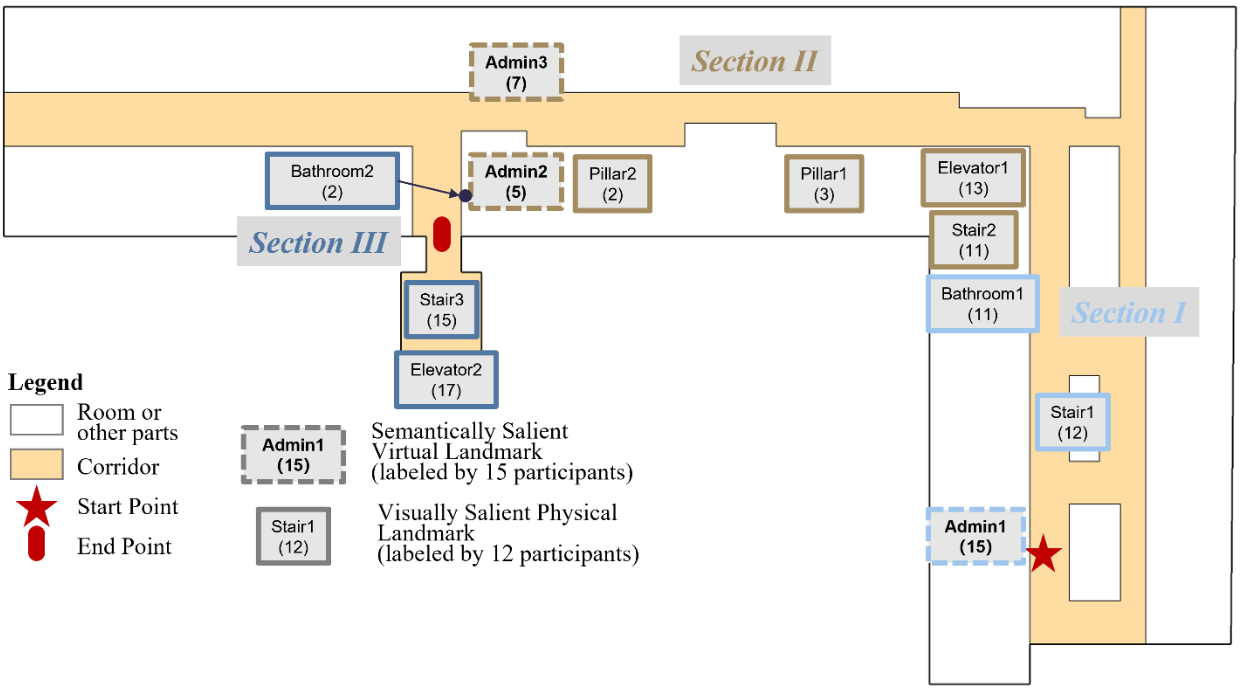


Figure 3-5 Landmarks considered in landmark locating tasks and results.

The results show that virtual semantic landmarks can assist the acquisition of corresponding knowledge even without learning intention, supporting **T4-landmark**. Such landmarks were most often labeled in the landmark locating task (only after the functional landmarks, stairs and elevators, Figure 3-5). In addition, individual cases show that HMD MR may influence not only the vision but also the height or the time perception of particular participants. These findings can be applied to facilitate the design of MR-based navigation interfaces and assist ordinary users' spatial learning.

3.4 SPATIAL LEARNING WITH VIRTUAL STRUCTURAL LANDMARKS AND ADAPTIVE DESIGN

The previous study (Section 3.3) confirms that virtual semantic landmarks shown as icons can assist incidental spatial learning of the semantic information during MR-based navigation. For structural information, **designers** usually implement iconic or pointlike landmarks as well. It remains to be answered if users can perceive the "structure" based on the pointlike holograms during incidental spatial learning and which other elements or visualizations the users think can assist their spatial learning. This study involves a user study and the DIY (design-it-yourself) tool development to collect **ordinary user**s' preferences for MR-based navigation interfaces, covering both **T4-landmark** and **T5-users**.

The user study in Section 3.2 is used as an integral part of this study. In the user study, we tested if users' spatial memory resembles the visualization and whether pointlike virtual structural landmarks can help users perceive the structure of the indoor environment. Pointlike landmarks were used to show the corridor nearby during navigation (Figure 3-6). The results show that most users can remember the augmented corridor incidentally. Seven out of 40 users cannot remember the corridor. We recommend using structural landmarks instead of pointlike landmarks for structural information for safety reasons, e.g., quick evacuation in an emergency.

Figure 3-6 Participants' view in the group with lines (left) and without lines (right).

Besides, the user study reveals the diverse users' preferences for interface design, and an adaptive/adaptable MR-based indoor navigation interface is needed. However, ordinary users' expectation of the MR-based navigation interface is not fully explored. Collecting their opinion by on-site HMD MR studies is costly and limits the number of accessed users. Therefore, we built the browser-based DIY tool (Figure 3-7a), which includes a first-person-view video of using HoloLens 2 navigating, photos of typical navigation scenarios, and adaptable icons (Figure 3-7b), to collect ordinary users' preferences of interface design. Twelve users used the DIY tool to design navigation interfaces. We analyzed their interface design, summarized their preferences, and generated examples of interface design (Figure 3-7c).

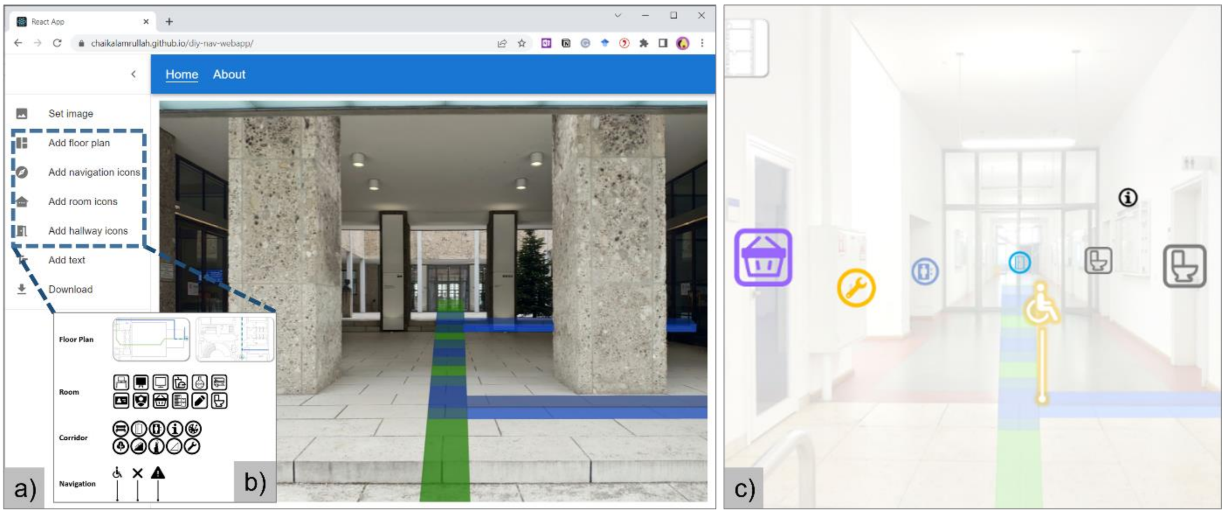
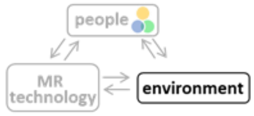


Figure 3-7 Design-It-Yourself tool. (a) the DIY interface, (b) the adaptable icon collection, (c) the generated interface design.

This study combines the **designer**'s and the **ordinary user**'s expectations of MR-based navigation, covering both **T4-landmark** and **T5-users**. The designer could help incidental spatial learning by interface design, and the ordinary user could propose more interface design solutions.

Collaboration between designers and ordinary users supports a better user experience in MR-based indoor navigation.

3.5 INFLUENCE OF ENVIRONMENTAL STRUCTURE ON VISUAL ATTENTION



The memory of structural information influences people's navigation behavior. Environmental structure *per se* also influences our attention distribution and spatial ability. Revealing how the **environment** affects users' intuitive attention distribution will improve the MR-based navigation interface design. It deepens our understanding of which information is needed and which position the info could be allocated. This study explores the gaze behavior differences influenced by environmental factors without MR and addresses **T7-attention**.

Road pattern is a well-known environmental factor strongly influencing spatial ability and learning. This study aimed to identify intuitive pedestrian gaze differences between regular and irregular road patterns for navigational tasks.

Twenty-one participants took part in this two-day user study. On Day 1, the participants were guided through two areas - one with a regular road pattern and another with an irregular road pattern (Figure 3-8) via the streetview map. On Day 2, they accomplished a set of orientation (ORI) and shortest route selection (SRS) tasks based on the previously learned areas (Figure 3-9). The eye movements during the D2 tasks were recorded by the Tobii T120 (Tobii AB, Stockholm, Sweden; www.tobii.com) eye tracker.

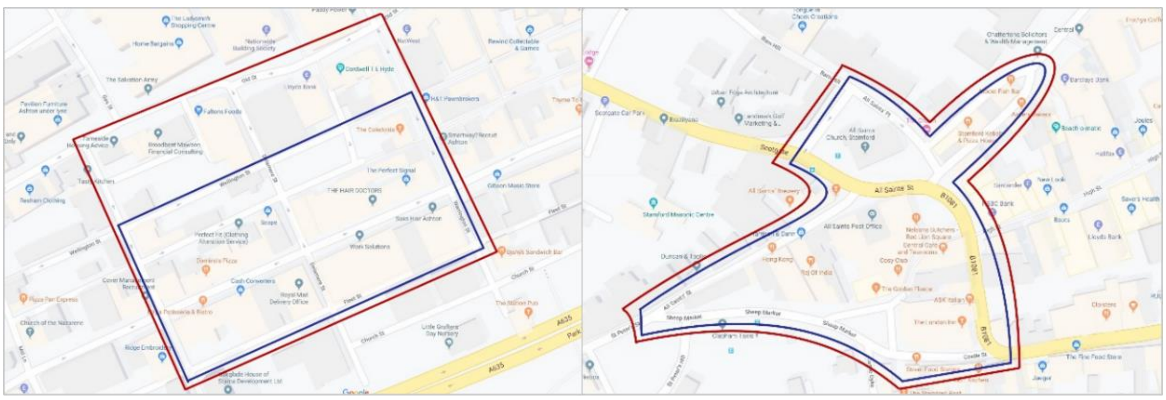


Figure 3-8 Study areas for regular and irregular road patterns. Left, Stamford, Lincolnshire; right, Ashton-under-Lyne, Greater Manchester. Red indicates the pre-test area, and blue represents the experimental areas; participants were not provided with these maps.

By analyzing eye movements over road and label information, we investigated the information essential for navigational tasks and the differences among distinct road patterns. Time to first fixation, average fixation duration, fixation count, and fixation duration (Table 3-2) on Label AOIs (area of interest) and Road AOIs (Figure 3-9) were analyzed.

Table 3-2 User study metrics.

Metric	Description	Unit
Time to First Fixation	Time spent before the AOI was first fixated on.	s
Fixation Duration	Total fixation duration within the AOI.	s/pixel number × 10,000
Fixation Count	Total fixation count within the AOI.	number/pixel number × 10,000
Average Fixation Duration	Fixation duration/Fixation count.	s

Figure 3-9 Example of user study stimulus and AOIs.

The results show the intuitive attention distribution in spatial tasks. The participants tend to rely on labels more for orientation and route selection, and roads with irregular patterns are essential. The findings answer **T7-attention** and indicate that labels and unique road patterns should be highlighted for better wayfinding and navigation. The results provide insights into the interface design for navigation applications.

3.6 Discussion and self-reflection

3.6.1 Findings of the publications

With the four journal publications and one additional contribution, the difficulty of spatial learning with MR-based navigation is tackled from the perspectives of developer, ordinary user, designer, and environment.

In the role of a **developer**, the researcher should consider where to store the spatial anchor (cloud/local) and how to generate the path (predefined/generated in real-time) according to the research question and the available resources in the study area. These approaches for prototyping are confirmed feasible in MR-based navigation research by the subsequent user studies from ordinary users' and designers' perspectives. We also propose a theoretical framework about developing the MR-based navigation, which serves as a reference for researchers to identify other possible relevant factors.

From the **ordinary users**' perspective, MR technology serves navigation well. The MR technology is attractive and intuitive to use. In most cases, ordinary users can learn the physical information during MR-based navigation correctly, even with conflicts between the physical and virtual visualization. Still, the slight misleading effect revealed in the current study could become more severe in more complex daily navigation settings.

The user studies confirm that **designers** could help preserve users' incidental spatial learning during MR-based navigation. The virtual semantic and structural landmarks may assist the learning of the corresponding spatial information. Ordinary users should be involved in MR-based navigation interface design and a web-based DIY tool is provided for this purpose. Developing MR-based navigation requires knowledge about the whole development framework and tools and is difficult for some designers and most ordinary users. Therefore, the interactions between the involved roles of MR-based navigation are necessary, e.g., to provide interface design opportunities to the ordinary users and involve active users in the interface design (Figure 3-10).

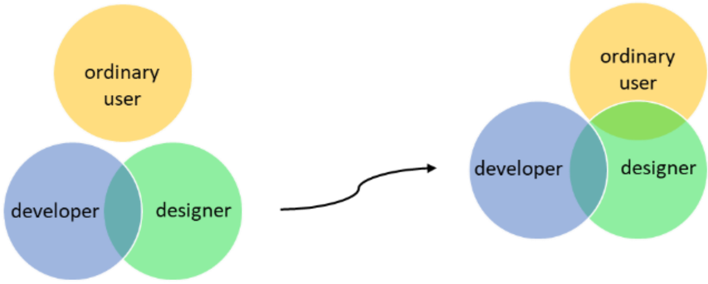


Figure 3-10 Change people's roles in MR-based navigation by involving ordinary users in the interface design.

Studying the **environment**'s influence on attention distribution shows that people rely on labels, and roads with irregular patterns are essential. For a more intuitive navigation experience, labels and unique road patterns should be highlighted in MR-based navigation.

3.6.2 Self-reflection

The findings of these five pieces of work have two main limitations.

The first limitation relates to the explorative nature of the current study. The research goal, i.e., to preserve and improve spatial learning during MR-based navigation, is approached exploratively from multiple perspectives. The developer, the designer, the ordinary user, and the environment are all covered, but the size of user samples and the study area are still limited. The study areas were smaller than the daily walking area. Some cognitive issues might be hidden for the long-time use of MR-based navigation and within certain user groups. User studies with a more extensive study area and more users are also necessary to examine the scalability of our current findings. Moreover, this work is motivated by the great potential of using HMD MR in indoor navigation. However, commercial and "fashionable" HMD MR devices are still rather young and have become available for no longer than one decade. The cognition or learning research about MR-based or first person-view navigation is still rare. The initial hypotheses were raised based on previous literature and findings, and some unexpected influences of MR-based navigation emerged on the way and need to be examined. For example, the sensing of non-existent stairs or the change of time flow in the study of virtual semantic landmarks (Section 3.3).

The second concern is about the potential for bias. In our studies, the users all expressed positive attitudes toward MR technology. This study confirms that incidental spatial learning during MR-based navigation is possible. However, we do not know if their affection for MR technology attracted them to pay more attention to the virtual holograms incidentally. If that was the case, we need to explore whether the incidental spatial learning is also possible for users who are less enthusiastic about the technology.

The conducted works in this thesis generally tackled the dilemma of spatial learning and navigation from a broad scope and generated preliminary and some unexpected findings. More systematic user studies about specific issues are necessary to deepen our understanding of HMD MR usage and its influence on navigation.

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4 Discussion and Outlook

4.1 Conclusion

This thesis aims to preserve and improve spatial learning during MR-based navigation. The MR technology evolves quickly, and the minimal viable MR-based navigation application is needed to understand user behavior and fulfill the urgent need for MR development. Three research questions are proposed in Chapter 1:

- **RQ1 -** How can we construct a minimal viable MR-based navigation application dedicated to studying user behavior?
- **RQ2 -** How far can proper visualizations help preserve or even improve incidental spatial learning during MR-based navigation?
- **RQ3 -** How is the users' attention influenced by environmental characteristics?

The research questions have been addressed with the following findings:

- **The development of the MR-based navigation application for user behavior study is driven by clearly formulated requirements and available sources in the study area.** Before building the MR-based navigation application for research purposes, we should clarify the **requirements**. The available sources in the study area should be tested to ensure free and smooth navigation. Besides, we proposed a **framework** for MR-based navigation application development. It is not only a workflow but can also be used to accelerate the development process. We must acknowledge that it is impossible to cover and discuss all relevant factors, and researchers will always face new challenges. With this framework, we provide researchers with a good reference and help them identify other factors which would influence the different parts of the whole process.

- **HMD MR users tend to integrate the virtual world with the real world during navigation, and responsible interface design is necessary.** Our findings suggest that the integration is both risky and promising. On the one hand, our study reveals the **risk** that the users' perception of the real world might be misled by the virtual visualization. If the interface of the MR-based navigation application is poorly, or even maliciously, designed, the user's memory of the physical world would be distorted, which may lead to real dangers. On the other hand, the users can also **benefit** from the integration. With good interface design, spatial learning can be preserved and improved during MR-based navigation. In our study, the users did not learn the space intentionally. Still, their memory of the information which was highlighted by the virtual semantic or structural landmarks was improved. Research on the interface design for MR-based navigation needs to be continued by including users in the design pipeline.

- **Users' visual attention is influenced by the environment, and the interface design should be adapted to the context.** People's spatial behavior and spatial ability are influenced by various environmental factors. Our study confirmed that users' eye movement distribution is different in regular and irregular road networks. The influence of other environmental factors on visual attention distribution is to be discovered. For better incidental spatial learning, the holograms should be placed close to users' visual focus. Thus, the interface design should take into consideration the **environment**. The **users' preferences** are diverse and need to be considered as well. In general, the interface design of MR-based navigation needs to be adapted to the context.

4.2 LIMITATIONS

In this thesis, we assume that the answers to the research questions are only related to people and the environment. In other words, the issues about spatial learning during MR-based navigation originate from the interaction between people and the environment. We focus on the developers, the ordinary users, the designers, and the environment (Chapter 3). However, we do not test whether the development of MR technology *per se* can be the solution to such cognitive issues.

The thesis approaches the research aim from various perspectives. The relationships among the developer, the designer, the ordinary user, and the environment are examined. The findings are based on three user studies. To what extent the findings hold true needs further evidence. For example, the user studies (Chapter 3, Section 3.2, 3.3, and 3.4) based on MR were conducted in 2020-2021, when the policy measures in response to the COVID-19 pandemic limited visits to the public building. While it assured a more controllable experiment condition than other times, the study area was less busy than it usually would be.

4.3 OUTLOOK

Navigation is an important application of MR technology. More research is required to improve our understanding of spatial learning with MR-based navigation and reveal the full potential of this technology. Besides navigation, other fields of geographic information science (such as architecture and building design, smart city, and facility management) can also benefit from MR.

Many follow-up studies of the current thesis are possible. The first direction is about **transferability**. In this thesis, the user studies about MR-based navigation are conducted within the same study area, i.e., the university campus. As mentioned in Chapter 2, indoor navigation is needed in various other indoor spaces, which are different from the university campus in terms of the visual distance, structural complexity, and visitors' expectations. Therefore, further experiments are needed to assess whether or how far users' learning differs in different indoor scenarios. Secondly, the **unsolved puzzles** are to be examined. A user recalled a slight slope as stairs in the user study about semantic landmarks (Chapter3, Section 3.3). While we assume this was due to his/her fear of heights, it is not proven based on currently available information. If that is indeed the reason, we need to investigate whether this also happens to other people who share this fear. These studies all require diverse study areas and different user groups.

With regard to the possibility of **intentional spatial learning**, the main issue is that the extra mental effort might discourage users and weaken the usability of the navigation assistance. Still, intentional learning could result in better spatial knowledge. With the further development of attractive MR technology, we could explore the possibility of balancing the workload and the amusement with the aim of encouraging active learning.

Collaboration among research groups, and among research and business teams are needed. Identifying a research question, developing the MR application, and designing, conducting, and analyzing the user study are time-consuming and demanding for one single researcher or group. Individuals or a small group of persons need to play different roles as a developer, a designer, and recruiters to find users for the user study. Distributing the tasks to different groups through collaboration would ease the burden and accelerate the research pace. For example, two research groups can take the development and design role separately, and the user study could be co-operated with business partners, e.g., the XR experience shop owners who easily access ordinary users.

For a more general research agenda, we believe new research questions will emerge as people and their behavior and perception of MR-based navigation evolve with technological development. For example, with more ordinary users having access to MR technology, more MR applications would be available. The interaction and collaboration among users and the competition between MR-based navigation applications and other applications should be explored to understand the influence of long-term usage of MR-based navigation assistance on spatial learning and spatial ability. Spatial ability is not limited to navigation or orientation; it is also about the ability to use the properties of space to communicate, reason, and solve problems, which is called spatial literacy. For example, would the increased incidental spatial learning cultivate a habit of spontaneously spatial learning and even improve spatial literacy? Such a question is more difficult to answer as it requires long-term tracking studies (e.g., years) with continuously changing factors.

In the long term, as people become accustomed to MR technology and “MR natives” mature, it remains to be studied whether or how far MR technology changes people’s perception of the physical world and how they see the two worlds.

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APPENDICES

APP.A LIU B, DING L, WANG S, MENG L (2022) DESIGNING MIXED REALITY-BASED INDOOR NAVIGATION FOR USER STUDIES. KN - JOURNAL OF CARTOGRAPHY AND GEOGRAPHIC INFORMATION.:1–10. DOI:10.1007/S42489-022-00108-4.

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Designing Mixed Reality-Based Indoor Navigation for User Studies

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Abstract
Mixed reality (MR) is increasingly applied in indoor navigation. With the development of MR devices and indoor navigation algorithms, special attention has been paid to related cognitive issues and many user studies are being conducted. This paper gives an overview of MR technology, devices, and the design of MR-based indoor navigation systems for user studies. We propose a theoretical framework consisting of spatial mapping, spatial localization, path generation, and instruction visualization. We summarize some critical factors to be considered in the design process. Four approaches to constructing an MR-based indoor navigation system under different conditions are introduced and compared. Our gained insight can be used to help researchers select an optimal design approach of MR-based indoor navigation for their user studies.

Keywords Mixed reality · Indoor navigation · Development approaches · User study

Die Gestaltung Mixed-Reality-basierter Indoor-Navigation für Nutzerstudien

Zusammenfassung
Mixed Reality (MR) wird zunehmend in der Indoor-Navigation eingesetzt. Bei der Entwicklung von MR-Geräten und Indoor-Navigationsalgorithmen wurde den damit verbundenen kognitiven Problemen besondere Aufmerksamkeit geschenkt, und es werden viele Benutzerstudien durchgeführt. Dieses Papier gibt einen Überblick über MR-Technologie, Geräte und das Design von MR-basierten Indoor-Navigationssystemen für Benutzerstudien. Wir schlagen einen theoretischen Rahmen vor, der aus räumlicher Kartierung, räumlicher Lokalisierung, Pfadgenerierung und Visualisierung von Anweisungen besteht. Wir fassen einige kritische Faktoren zusammen, die im Designprozess berücksichtigt werden müssen. Vier Ansätze zum Aufbau eines MR-basierten Indoor-Navigationssystems unter unterschiedlichen Bedingungen werden vorgestellt und verglichen. Unsere gewonnenen Erkenntnisse können genutzt werden, um Forschern bei der Auswahl eines optimalen Designansatzes der MR-basierten Indoor-Navigation für ihre Benutzerstudien zu helfen.

1 Introduction

People nowadays spend most time indoors (Klepeis et al. 2001). Among many indoor activities, human often need to navigate themselves to certain places. Yet indoor navigation is a complicated task and is regarded as more difficult than outdoors (Bauer et al. 2015, 2016). People get lost more easily within complex public buildings (Fellner et al. 2017), such as universities,[1] libraries, retail, manufacturing, airports, and hospitals. Many factors lead to the difficulties in identifying directions, for example, indoor structures vary among buildings, and walls may hinder the view (Aksoy et al. 2020; Holscher et al. 2007). Moreover, visitors are sometimes under time pressure, which has a negative effect on navigation. Bartling et al. (2021) demonstrated this negative effect in their study where people were asked to go to specific room under time pressure for an interview.

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[1] Steerpath Kiosk Maps (2021). https://kiosk.steerpath.com/aalto/index.html. Accessed 28 March 2022.

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However, due to the challenges of indoor positioning, e.g. the difficulty of getting stable GNSS (global navigation satellite system) signal for navigation, indoor navigation assistance is still limited. Emerging devices and technologies commonly used for indoor navigation are Beacons, Wi-Fi, and visual positioning system (VPS). Mixed reality (MR) technology, which augments real world by displaying virtual holograms and introducing additional information, is promising for indoor navigation. Despite some MR-based indoor navigation systems implementations, many cognitive issues, such as attention distribution (Bolton et al. 2015), spatial perception (Keil et al. 2020) and spatial learning (Liu et al. 2021), remain unanswered for better user experiences of MR-based indoor navigation. Research has been conducted to address these cognitive issues (Joshi et al. 2020; Liu et al. 2021; Rehman and Cao 2017). Developing MR applications, including MR-based indoor navigation applications, with comprehensive functions can be difficult (Rokhsaritalemi et al. 2020). However, not all the functions are necessary for research purposes. Different approaches can be applied to create MR-based indoor navigation demos for specific research purposes. A proper approach can accelerate the development of the application and the research of MR-based indoor navigation.

In the following sections, we first briefly introduce indoor navigation and navigation assistance, MR technology, and available devices and software. The second section summarizes a framework of designing an MR-based navigation system and the critical factors to be considered, especially for the design of experimental systems involving user studies. Then four different approaches for research purposes and user studies (rather than commercial use or end-user applications) are presented with examples in the third section. We also highlight the pros and cons of each approach along with its applicability. Our findings are summarized, and the future work is presented in the final section.

1.1 Indoor Navigation and Navigation Assistance

Many people find it difficult to navigate in public buildings, which are often complex in design. The visual access is limited within such buildings (Holscher et al. 2007). The symmetric structure of buildings increases the difficulty of distinguishing the floors and parts for navigation (Aksoy et al. 2020; Holscher et al. 2007), and people tend to assume the layouts of different floors are the same (Carlson et al. 2010). The furniture and functions of rooms in the buildings usually help the visitors identify floors or sections in such cases, but they can be easily and frequently changed, which makes it difficult for visitors to establish stable anchor points in indoor spaces. Besides, most people visit these buildings only a few times, and the first-time visitors usually go to a building for specific purposes under time pressure, which makes way finding even more stressful (Bartling et al. 2021). All these factors indicate that the daily indoor navigating is not a trivial task.

However, not much indoor navigation assistance is available (Joshi et al. 2020). The main bottlenecks are indoor positioning and accessibility calculation. Current options of indoor positioning include blue-tooth and Wi-Fi signals. MR technology is increasingly used in indoor navigation. MR devices can get the 3D position from simultaneous localization and mapping (SLAM) and require no additional hardware. This means that MR does spatial mapping and spatial positioning without GNSS. MR technology has some typical difficulties in mapping transparent objects and displaying holograms under strong lighting conditions, which is less problematic for indoor navigation. Therefore, MR is potentially suitable for indoor navigation and some companies already provide MR-based navigation service (e.g. XRGO,[2] Tangar[3]).

MR for research purposes is different from that for commercial use. For example, the MR device Microsoft HoloLens 2 supports eye control, providing an interesting and promising interaction method for common users. However, its eye movement data is not ready to be accessed. Kapp et al. (2021) developed ARETT, an easy-to-use toolkit for MR HMDs to get the eye movement data for scientific researches. Creating MR-based indoor navigation for research is also different from that for commercial applications. A commercial application must function properly for the entire indoor space and should be easy to use for common users, while for research purpose, a predefined path could be enough but might require more manual settings from the researcher. The specific requirements for the built navigation application vary with research questions. Some research questions are related to the current technology and become less problematic as the technology matures, e.g., the discomfort caused by the heavy weight. Other research questions are more basic and remain to be addressed, e.g., inattentional blindness in MR-based indoor navigation (Wang et al. 2021). For different research purposes, various approaches are available for MR indoor navigation development, and the workflow should be adjusted according to the research aim to meet the requirements.

1.2 MR Technology and Research

The term mixed reality became popular when the HoloLens 1 was launched by Microsoft. Prior to that, mixed reality was used to refer to both virtual reality and augmented reality (Milgram and Kishino 1994). Currently, *augmented*

[2] XRGO (2021) XRGO|We connect the industry with X-Reality (AR, MR, VR). https://xrgo.io/en/. Accessed 28 March 2022.

[3] Tangar—Indoor navigation using Computer Vision and AR (2021) Home—Tangar—Indoor navigation using Computer Vision and AR. https://tangar.io/. Accessed 28 March 2022.

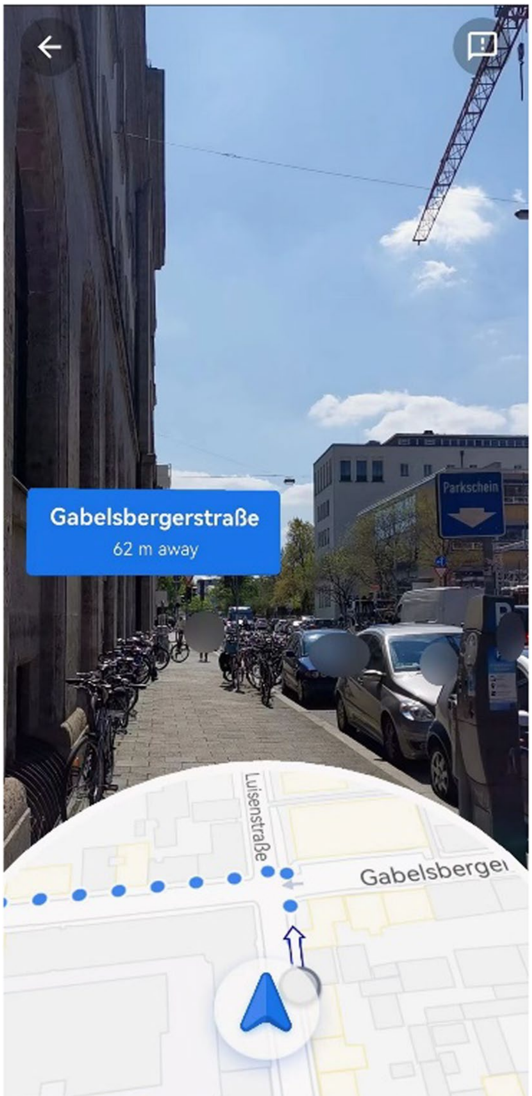

Fig. 1 Example of HHD MR, Google Maps "Live View" shown on a smartphone

reality and *mixed reality* both refer to the technology that displays virtual holograms and the real world simultaneously (Çöltekin et al. 2020). This paper uses *mixed reality* for both mixed reality (as Microsoft refers to) and augmented reality. Current MR devices are mainly hand-held (HHDs, i.e., smartphones), head-mounted devices (HMDs), and head-up displays (HUDs).

1.2.1 Hand-Held Devices

Most smartphones and tablets support MR. The HHD MR displays the augmented virtual holograms on the screen (Fig. 1) and is pretty attractive for consumers. Some indoor MR navigation apps are already available for smartphones (such as XRGO[4] and INDOAR[5]). However, with HHD MR, users need to switch their visual attention between the device and the environment (Stähli et al. 2021). The high cognitive workload may lead the users to ignore the potential dangers. Besides, it is not practical for multi-tasking users to hold the smartphone in their hands all the time.

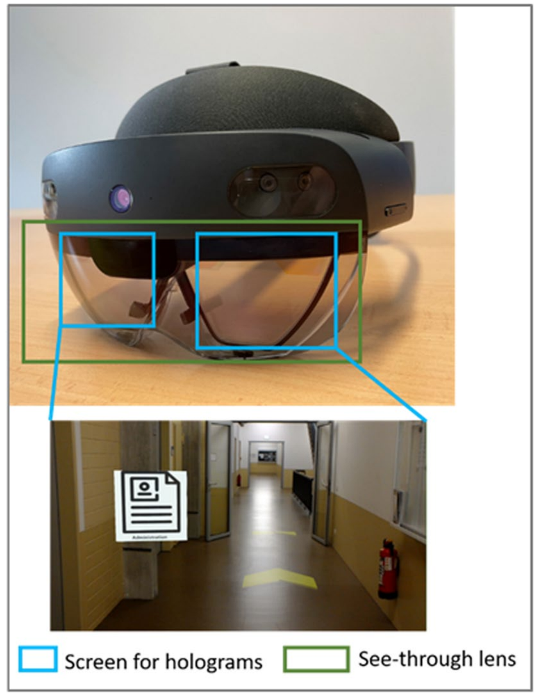

Fig. 2 Example of HMD MR, Microsoft HoloLens 2

1.2.2 HMD MR Devices

Microsoft HoloLens and Google Glass are among the current most widely used HMD MR devices. Users wearing the goggles/helmet can see the augmented virtual elements displayed on the lenses (Fig. 2). Other MR HMDs, such as Acer,[6] HP,[7] and Lenovo Explorer,[8] are seldom used and

[4] XRGO (2020) Augmented Reality Indoor Navigation App for iOS or Android | XRGO. https://xrgo.io/en/product/ci-inplace/. Accessed 28 March 2022.

[5] INDOAR (2022) INDOAR for Museums | Guided Tours & Immersive Experiences with augmented reality | ViewAR. https://museum.viewar.com/. Accessed 28 March 2022.

[6] Acer (2022) Windows Mixed Reality Headset. https://www.acer.com/ac/en/US/content/series/wmr. Accessed 28 March 2022.

[7] HP (2022) HP Windows Mixed Reality Headset | Discover a new level of immersion—HP Store Schweiz. https://www.hp.com/ch-de/shop/offer.aspx?p=c-mixed-reality-headset. Accessed 28 March 2022.

[8] Lenovo (2022) Lenovo Explorer | Headset for Windows Mixed Reality | Lenovo UK. https://www.lenovo.com/gb/en/smart-devices/virtual-reality/lenovo-explorer/Lenovo-Explorer/p/G10NREAG0A2. Accessed 28 March 2022.

Fig. 3 Example of HUDs, screenshots of video by Phiar, **a** displayed on windshield, **b** displayed on extra screen with real-time camera stream

1.2.3 HUDs

HUDs have been equipped in many cars in form of MR dashboards such as MBUX AR in Benz and Phiar. The augmented virtual elements are either displayed on the windshield directly (Fig. 3a) or an extra screen with real-time camera stream (Fig. 3b). An HUD performs spatial mapping differently from HMD and is beyond the focus of this paper.

1.3 MR Software Options

Many software options are available to develop MR products and new toolkits are being developed. Here, we briefly introduce the most commonly used software and strongly recommend readers to explore their functionality and services. Unity and Unreal are commonly used and applicable on different platforms. MR indoor navigation can be built with ARKit (for iOS), ARCore (for Android and iOS), or Mixed Reality Toolkit (MRTK, for windows, mixed reality HMD, Android, and iOS). Many companies also provide Software Development Kits to facilitate the development. WebXR is just an example.[9] The navigation module such as Mapbox Vision AR for Android is also provided.

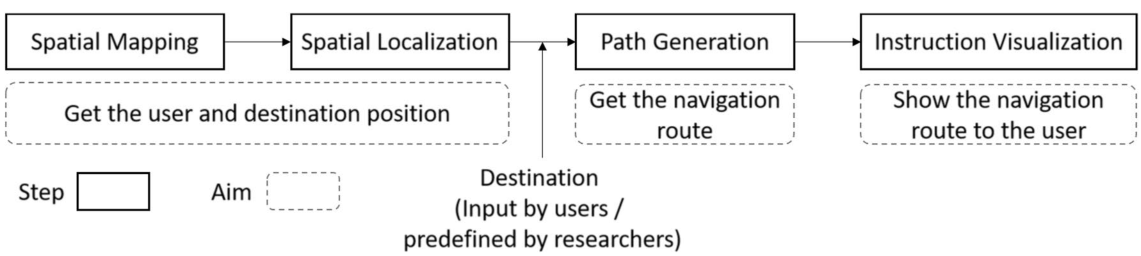

Fig. 4 A general framework of how to design MR-based navigation system

not quickly updated. The HMD MR is valued in pedestrian navigation, and the associated cognitive issues are widely studied (Liu et al. 2021; Makimura et al. 2019; Thi Minh Tran and Parker 2020). Some studies aim to find solutions constrained by the current technology, e.g., how to arrange the virtual holograms within the limited field-of-view (FOV) (Kishishita et al. 2014), while other issues related to user behavior need long-term investigation, e.g., users pay too much attention to virtual holograms and ignore the events in the real world (Krupenia and Sanderson 2006; Wang et al. 2021).

2 Methodology

2.1 A Development Framework of MR-Based Navigation System

Given the current location of the user and his/her destination, the MR-based navigation system should be able to generate the navigation path and display it to users. Figure 4 illustrates a framework of designing an MR-based navigation system.

[9] WebXR (2021) Immersive Web Developer Home. https://immersiveweb.dev/. Accessed 28 March 2022.

Table 1 Comparison of four approaches

	Internet connection is required	BIM is required	Anchor position is stable	The path generated is flexible	Can be shared across multi devices	Suitable for the big study area	Required coding ability is
LA-PP	No	No	No*	No	No	No	Low
LA-GP	No	Yes	No*	Yes	No	No	High
CA-PP	Yes	No	Yes	No	Yes	No	Medium
CA-GP	Yes, strongly	Yes	Yes	Yes	Yes	Yes	High

*It is possible to build persistent and stable local spatial anchors across runs, e.g. an approach by Nischita.[12] However, it is not the official and recommended way and might be more difficult in the future. Therefore, it is omitted in this paper

2.1.1 Spatial Mapping

Spatial mapping prepares the model/map of the indoor environment needed to generate the path to an indoor location, which is usually beyond sight. The MR device maps the real world surfaces in the nearby environment. It has the potential to automatically generate a building information model (BIM) (Hübner et al. 2019). Standard models for better indoor navigation are also being developed. For example, IndoorGML version 1 was released in 2014, partially inspired by the urgent requirements from indoor navigation (IndoorGML OGC 2020). The destination needs to be defined by users or predefined by researchers.

2.1.2 Spatial Localization

Spatial localization gets the user's current location. It can be based on visual/image markers, beacons, or visual positioning system (VPS) (badmin 2020).

2.1.3 Path Generation

Path generation is the process of creating a walkable path from the start point to the destination. Many algorithms are available for indoor navigation path planning, such as Dijkstra's algorithm (Fan and Shi 2010), A* (Wang and Lu 2012), and so on.

2.1.4 Instruction Visualization

Once the path is generated, it will be displayed together with navigation instructions visually (Huang et al. 2012; Liu et al. 2021) and/or audibly (Fellner et al. 2017; Huang et al. 2012). Instruction visualization as the process of determining which instruction to display and how to display is also crucial for MR-based indoor navigation systems (Cock et al. 2019; Liu et al. 2021; Liu and Meng 2020).

2.2 Design Factors for User Study

Many factors need to be considered when designing an MR indoor navigation system for user studies. For example, the study area should be easily accessible and safe for the users and ideally have constant lighting conditions to ensure stable visualization (holograms are difficult to see under strong lighting) and comparable results among users. Liu and Meng (2020) summarized relevant factors in this regard.

Besides, the interface design might better be inclusive, e.g., considering the need from color-blind or visually impaired users (Qiu 2019). The interface or algorithm should also run smoothly without exceeding the computing power of the devices (Curtsson 2021).

3 Design Approaches of MR-Based Indoor Navigation Systems for User Studies

When choosing an approach for developing MR-based navigation, at least two factors need to be considered: (1) spatial anchor and (2) path generation. A spatial anchor is a fixed coordinate system that is generated and tracked by MR, and ensures the anchored holograms are located in the precise location.[10] In an MR-based navigation system, the spatial anchor can be a local (LA, stored in the device) or a cloud (CA, stored on the cloud, e.g. Azure Spatial Anchor[11]) one and the path can be predefined (PP) or generated during the navigation (GP). Therefore, four approaches are feasible in developing the system. They are compared regarding

[10] Microsoft (2021), Spatial anchors, https://docs.microsoft.com/en-us/windows/mixed-reality/design/spatial-anchors. Accessed 25 April 2022.

[11] Spatial Anchors (2022), Azure Spatial Anchors | Microsoft Azure. https://azure.microsoft.com/en-us/services/spatial-anchors/#features. Accessed 28 March 2022.

[12] Nischita (2020), Anchoring Objects with Local Anchors and Persisting with HoloLens 2, https://codeholo.com/2020/09/24/anchoring-objects-with-local-anchors-and-persisting-with-hololens-2/. Accessed 25 April 2022.

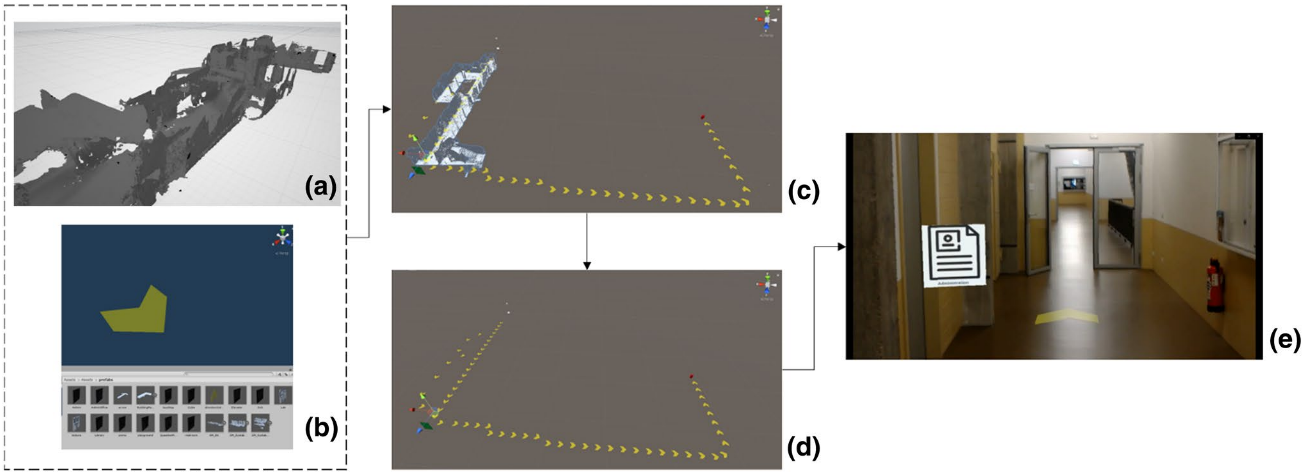

Fig. 5 Workflow of the example LA-PP approach. **a** Spatial mapping result from HoloLens. **b** Prefabs viewed in Unity. **c** Overlay of spatial mapping result to set the prefabs as the path. **d** Overview of the redefined path. **e** User's view from the start point

the requirements of materials, resources, and performance (Table 1). We also give examples of each approach.

3.1 Local Anchor–Predefined Path Approach

In this approach, local spatial anchors and predefined paths are used. Spatial anchor is stored on the device and cannot be shared across multiple devices. It is loaded and manually anchored by the user to a new position each time the software runs. In this case, internet connection and BIM are not required, and the anchor position changes, even slightly, between different runs or if multiple devices are used in the research. Applying only one spatial anchor would reduce the time and workload of anchoring but may increase localization errors. Therefore, the number of necessary anchors relies on the study area and research questions.

A predefined path does not mean that only one path is available. It is possible to set multiple destinations/paths during development. However, once deployed, the paths are set, and the visualization cannot be changed. For example, the path cannot be changed to avoid a passer-by. Besides, since all the holograms are locked to one anchor, the errors are cumulating, i.e., the farther the hologram is away from the anchor, the larger the misalignment would be. The anchor should be in the middle of the whole study area instead of the start point, and the study area should not be too big. It is an immediate and low-code requirement to build. Therefore, this approach is suitable for a quick assessment of the interface and elements design and fast feedback on cognitive issues. It is also convenient for the research that must be done without the internet. This workflow suits beginners and small projects or rapid prototyping. However, since it requires manual anchoring, it is unsuitable for research involving large user groups.

3.1.1 Example. Building with Local Spatial Anchor and a Predefined Path

This example uses a local spatial anchor and predefined path to create an indoor navigation demo, which was used to test spatial learning during navigation (Liu et al. 2021). It was built using Unity, MRTK, and HoloLens 1.

Figure 5 shows the workflow in this example. Although BIM is not mandatory, HoloLens is used to create a rough model of the study area and map the layout (Fig. 5a). It allows the researcher to put the holograms in the correct position. A floor map also helps to show the number of turns, length, etc.

The holograms should also be prepared (Fig. 5b). In this case, pictorial landmarks and arrows are used. MRTK provides basic GameObjects, such as cubes, spheres, arrows, etc. The pictorial landmarks are generated from png-format pictures. The png. files are used as the material of the basic GameObjects, and the size of GameObjects can be adapted. The GameObjects can also be attached with scripts and then made into prefabs for re-use. For example, when users are moving around, the landmarks should always face the users to remain identifiable. This function can be realized by the *billboard* provided by MRTK. The prefabs can be located according to the model (Fig. 5c, d) or the floor map. At the beginning of the user study, the researcher needs to set the spatial anchor manually. It is recommended that the researcher walk through the whole study area and ensure the misalignment is acceptable. The user's view is shown in Fig. 5e.

This demo used one spatial anchor at the middle point of the path (Fig. 6). The spatial anchor is a rectangle instead of a point to allow the alignment both horizontally and vertically with the real world and make sure the direction of the

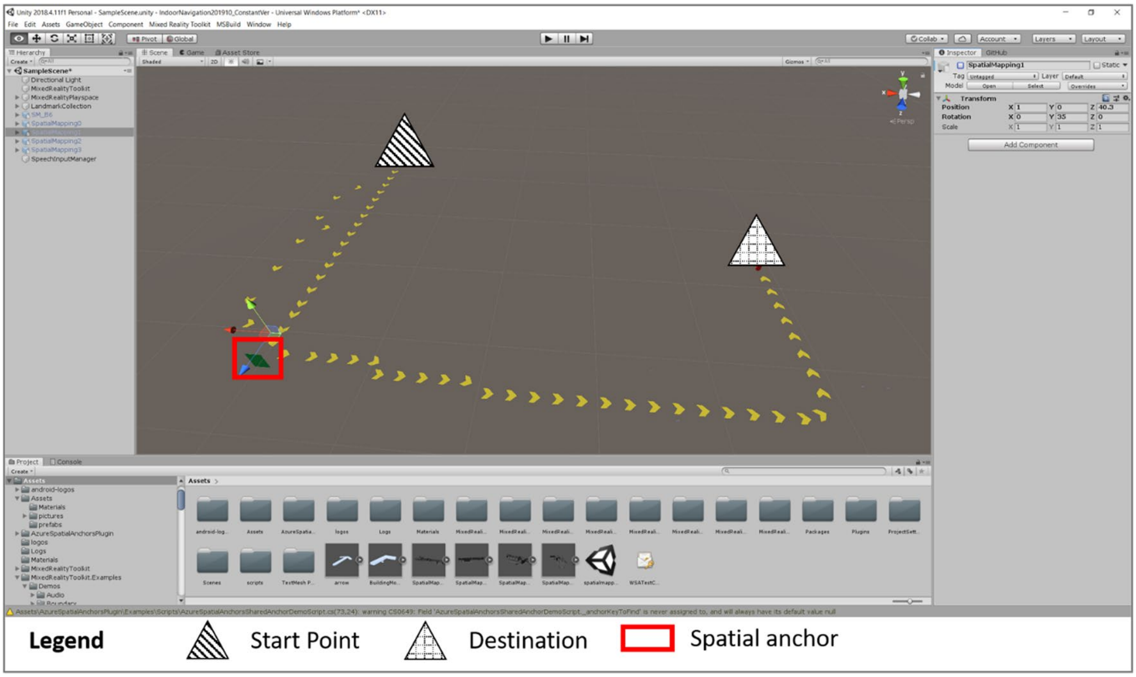

Fig. 6 The location of local spatial anchor in a predefined route

whole path is correct. The anchor was designed in grey and transparent so that it does not affect the users' navigation. This design proved effective as most users did not notice this anchor.

3.2 Local Anchor–Generated Path Approach

Like the LA-PP approach, the LA-GP approach does not require an internet connection, the spatial anchor is not constant for each user, and cannot be shared across devices. This means the visualization of the spatial anchor should also be big enough for accurate localization. This approach is also not ideal for studies with an extensive study area or large user groups. BIM is required so that the location of destination is known and can be used in path generation. This approach is more flexible and suitable for exploring interaction and dynamic situations, for example, how users can find the preferred route or avoid obstacles.

Different from the LA-PP approach, in the LA-GP approach, a path between two locations can be generated according to the users' command by a path generation algorithm. This allows users to set their preferred destinations or avoid obstacles in real time. However, BIM is needed to generate the path, and it requires higher coding ability to integrate the path generation algorithm in the demo.

One example of the LA-GP approach is the work of Qiu (2019) using Unity, Holo Toolkit (the predecessor of MRTK), and HoloLens 1, with the aim to design an indoor navigation system that can avoid obstacles in real-time. A* search algorithm and BIM were used. The indoor space was segmented into many nodes. Once the user set a destination by hand gesture or voice control, the software generated a path. During walking, the HoloLens constantly maps the spatial environment and checks if there are obstacles (e.g., a passer-by) on the following paths. If so, the path will be re-calculated to avoid the obstacle.

3.3 Cloud Anchor–Predefined Path Approach

The resources required in the CA-PP approach are similar to those in the LA-PP approach. The BIM and path generation algorithm are not necessary. However, it requires an internet connection. The holograms are anchored to an online anchor, e.g., Azure Spatial Anchor. A cloud spatial anchor module is needed to upload and download the anchor to/from the cloud. Therefore, it needs more codes and requires higher coding capability compared to the LA-PP approach. The positions of holograms remain the same across sessions, which spares the effort of setting the spatial anchor each time. The spatial anchors can be shared by different devices and thus multiple users can collaborate. Besides, since the paths are predefined, the holograms can be locked to one spatial anchor. In this case, once the spatial anchor is set, no internet connection is necessary. However, if multiple spatial anchors are used, a stable internet connection is necessary. Therefore, the CA-PP approach is suitable for user studies that may last for a long time, involve many users and are with limited internet connection.

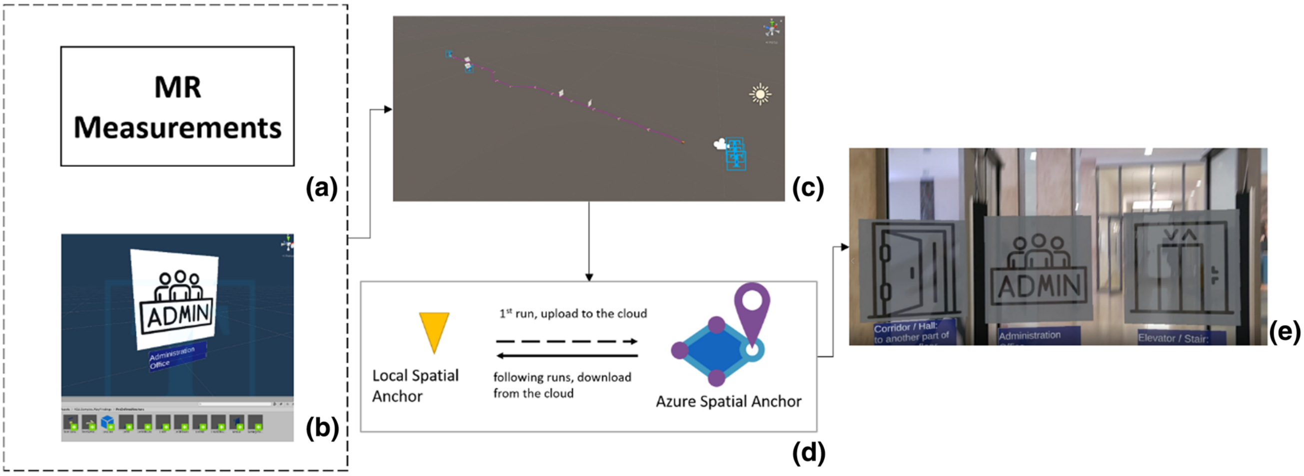

Fig. 7 Workflow of the CA-PP example. **a** MR measurements of the study area are used. **b** Prefabs viewed in Unity. **c** Predefined path. **d** Upload and download the local spatial anchor to/from the cloud. **e** User's view from the start point

Figure 7 shows an example using the CA-PP approach for building MR-indoor navigation. In this demo, Unity, MRTK, and HoloLens 2 were used. The layout was measured by MR measure apps on a smartphone (Fig. 7a). The holograms (Fig. 7b) and path (Fig. 7c) are designed similarly to those in the LA-PP example. The main difference is that the spatial anchor is uploaded to the Azure platform on the first run. Afterward, the spatial anchor can be loaded in each session (Fig. 7d). Therefore, the spatial anchor is not necessarily at the middle point and can be set at the start point or endpoint. Figure 7e shows the user's view at the start point.

3.4 Cloud Anchor–Generated Path Approach

The abovementioned three approaches can fulfill the requirements of most studies. However, the paths generated in those approaches are usually not very long to allow stable visualization, which cannot reveal cognitive issues that might only occur during more extended usage of MR-based indoor navigation (Curtsson 2021). Besides, some cognitive issues may occur during intensive interactions among different users (Liu et al 2021). The CA-GP approach has the advantage for applications in a bigger study area and with many users.

In this approach, the path generation algorithm and BIM are needed. A stable, constant internet connection is necessary for a smooth navigation experience. Since the spatial anchors are saved online, no BIM is needed. A possible solution is to provide two-player roles. The first role is for the researcher, who needs to walk around, set and upload spatial anchors to the cloud and edit the properties. The second role is for the users to set destinations and navigate themselves. Takahiro Miyaura provides an example.[13] In this project, the user can create different paths and upload them to the cloud interactively and find the path to a specific destination afterwards.

4 Conclusion and Outlook

This paper introduces a general framework using MR technology for indoor navigation assistance. To design an MR-based indoor navigation system for research, especially for user studies, we analyzed four approaches based on whether the spatial anchor is local or on the cloud and whether the path is predefined or generated in real time. We recommend the beginners/non-developers to use local spatial anchor and predefined design, which is less flexible but with a low demand of coding capabilities. We also recommend to use this approach for study areas without internet connection. But the spatial anchor needs to be set manually, making it less suitable for large groups of users. For research involving many interactions, we recommend to use the local anchor and path generation in real time, since this approach is more flexible. As for studies involving many users, using cloud anchor in combination with the predefined path is feasible. To study the cognitive issues after a long walking distance or with intensive interaction among different MR users, cloud anchors should be used, and the path should be generated dynamically.

[13] Takahiro Miyaura (2022) WayFindingSamplesUsingASA. https://github.com/TakahiroMiyaura/WayFindingSamplesUsingASA. Accessed 28 March 2022.

Current indoor navigation is mostly studied in simplified environments with a single building or connected buildings, which significantly restricted the transferability of research findings. User-friendly navigation services are needed for more realistic settings with complex buildings and integrated indoor and outdoor environments. This paper assists researchers in selecting a proper approach for the development of a research-oriented MR-based indoor navigation system in more general environments.

Building a fully functional commercial MR-based indoor navigation is complex and requires a lot of efforts. However, a workable research-oriented MR-based indoor navigation system is much easier to build. With the limited but necessary functionalities, they support the exploration of cognitive issues in MR-based navigation, improve our understanding and accelerates the application of MR technology, and improves the MR user satisfaction.

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Misleading effect and spatial learning in head-mounted mixed reality-based navigation

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ABSTRACT

Mixed Reality (MR) technology has been increasingly used for navigation. While most MR-based navigation systems are currently based on hand-held devices, e.g., smartphones, head-mounted MR devices have become more and more popular in navigation. Much research has been conducted to investigate the navigation experience in MR. However, it is still unclear how ordinary users react to the first-person view and Field of View (FOV)-limited navigation experience, especially in terms of spatial learning. In our study, we investigate how visualization in MR navigation affects spatial learning. More specifically, we test two related hypotheses: incorrect virtual information can lead users into incorrect spatial learning, and the visualization style of direction can influence users' spatial learning and experience. We designed a user interface in Microsoft HoloLens 2 and conducted a user study with forty participants. The user study consists of a walking session in which users wear Microsoft HoloLens 2 to navigate to an unknown destination, pre- and post-walking questionnaires, sketch map drawing, and a semi-structured interview about the user interface design. The results provide preliminary confirmation that users' spatial learning can be misled by incorrect information, even in a small study area, but this misleading effect can be compensated by considerate visualization, e.g., including lines instead of using only arrows as direction indicators. Arrows with or without lines as two visualization alternatives also influenced the user's spatial learning and evaluation of the designed elements. Besides, the study shows that users' preferences for navigation interfaces are diverse, and an adaptable interface should be provided. The results contribute to the design of head-mounted MR-based navigation interfaces and the application of MR in navigation in general.

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1. Introduction

Mixed Reality (MR) or Augmented Reality (AR) technology allows users to simultaneously perceive the real physical world and virtual digital holograms. Experiences with MR are quite pleasing to most users and thus highly valued in various fields, such as education, manufacturing, and gaming. Location-Based Service (LBS) and navigation also benefit a lot from MR. For example, the well-known location-based game Pokémon Go was downloaded over 10 million times on hand-held devices within a week of its release in 2016. “Live View” AR walking directions launched by Google in 2019 is not only entertaining but also helps users orientate in complex situations, e.g., when leaving an unfamiliar subway station and unsure which way to go. More recently, the emerging head-mounted MR (hm-MR) is attracting more attention in LBS and navigation, as it creates a highly immersive experience, frees up the hands, and allows users to multitask.

Theoretically, the hm-MR mitigates some issues of current hand-held MR (e.g., the Live View in Google Maps on smartphones). The hand-held MR device is inconvenient and may distract users. For example, for safety reasons, Google Maps suggest the Live View users to put away the smartphone once they figure out the direction[1]. This is less likely an issue for hm-MR as it includes the virtual objects in users’ daily normal Field of View (FOV) and keep them aware of the physical environment (Tran and Parker 2020). However, some user studies indicate that users may be overwhelmed by or obsessed with the new hm-MR experience and tend to ignore the physical world (Liu, Ding, and Meng 2021). Such inattentional blindness (see *1.1. Inattentional blindness and its influence in mixed reality*) can weaken spatial learning (Brügger, Richter, and Fabrikant 2019; Gramann, Hoepner, and Karrer-Gauss 2017; Ruginski et al. 2019). Besides, if the hm-MR fails mapping the space (i.e., spatial mapping), users may be guided to wrong places. For example, the current hm-MR has difficulties mapping transparent objects, such as glass, and might lead users to step on them. Ignorance of the real physical world may even be fatally dangerous in some navigation situations. Even if the hm-MR corrects itself early enough, it is not clear whether such errors lead users to wrong spatial learning.

In this paper, we investigate how hm-MR-based navigation visualization influences users’ perception and spatial learning. Specifically, we test whether incorrect information mislead users and whether the visualization of direction indicator affects users’ spatial learning.

1.1. Inattentional blindness and its influence in mixed reality

Inattentional blindness is common in our daily life. It refers to the situation where we ignore the object that are in the plain sight and fails to notice the existence of an unexpected item (Jensen et al. 2011). A slight distraction can cause inattentional blindness and hinder the main task. For example, phone usage during walking can lead to inattentional blindness during tasks with just low cognitive demands (Hyman et al. 2010). We do not just ignore trivia objects but also the safety relevant visual stimuli (Murphy and Greene 2015).

Increased inattentional blindness is found in MR. It is not surprising since people get distracted by many objects/events, and the entertaining, novel and sometimes interactive holograms in MR are definitely one of them. Krupenia and Sanderson (2006) found the participants performed worse at detecting unexpected events wearing hm-MR. In McNamara, JR.’s report (accessed 2022) about a user study trying to take advantage of the

[1] “Use Live View on Google Maps - Android - Google Maps Help.” 2022. Accessed August 18, 2022. https://support.google.com/maps/answer/9332056?hl=en&ref_topic=3292869#%20zippy=%2%20Cnavigate-with-live-view.

inattentional blindness on education, he used hm-MR to keep the users focusing on the virtual content and less distracted by the real-world event. However, he found no significant difference in task performance between users using hm-MR and those using laptop. More recently, inattentional blindness has been confirmed in monitor-based AR (Dixon et al. 2014) and Augmented Reality Head-Up Display (AR HUD, Wang et al. 2021). There is no clear conclusion on whether such inattentional blindness also exists in current more developed hm-MR. However, in the study of Liu, Ding, and Meng (2021), when using hm-MR the participants tended to ignore the unaugmented physical elements, similar to how participants behaved with AR HUD as reported by Wang et al. (2021).

In fact, despite the entertaining experience, hm-MR might reduce user's spatial awareness. A common criticism of current hm-MR is the limited FOV. Usually, it's only the screen for holograms that is with limited FOV, e.g. the screen for Microsoft HoloLens 2 is 43°×29° (Heaney 2019), but the rest is with lens and allows users to see the real world (Figure 1). However, users' attention tends to be attracted by holograms and limited to the screen. In such situation, the peripheral vision might decrease. For normal-sighted people in physical world, the negative influence on spatial learning occurs only with extremely limited FOV (Barhorst-Cates, Rand, and Creem-Regehr 2016). In Virtual Reality (VR), restricted FOV does not impede spatial learning either (Adhanom et al. 2021). But these findings are based on pointing tasks or object placement tasks, it is not clear whether spatial learning of objects on sideways is affected.

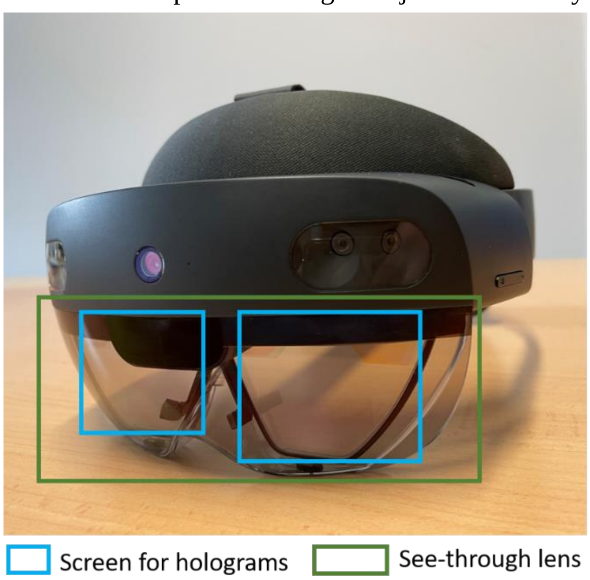


Figure 1. Microsoft HoloLens 2, blue: screen for holograms; green: see-through lens.

The inattentional blindness can interfere with navigation and spatial learning and might impair users' spatial ability in a long run. Users' visual attention and spatial awareness are critical to navigation success and enhanced spatial learning (Kapaj, Lanini-Maggi, and Fabrikant 2021). With "traditional" navigation aids, such as being led by other people, or using smartphones, users are less attentive to the route and usually do not learn the space well (Stites, Matzen, and Gastelum 2020). With hm-MR, the users are even more attracted by the navigation aid, i.e., the virtual visualization, which may lead to a decreased perception of the real world (McKendrick et al. 2016) and a loss of essential information for safe navigation. In the long run, users' spatial ability may also suffer. Therefore, many researchers are trying to use as few and simple holograms as possible for the MR visualization and retain the users' spatial awareness (Bolton, Burnett, and Large 2015; McKendrick et al. 2016; Rehman and Cao 2017).

The inattentional blindness raises another concern of whether users can perceive the real physical world correctly if the virtual world conflicts with the real one. Navigation aids need to keep the users physiologically safe and not misled by the navigation aid (Fang, Li, and Shaw 2015). The current first-person-view navigation in hm-MR is with limited FOV and immersive experience. Whether the virtual objects or environments could override the perception of real world and thus mislead users is not clear yet. For example, if the device fails in real-time spatial mapping and direct the user to an inaccessible zone. This is important since if the virtual world overwrites the physical world, it may confuse the users afterwards and cause much pain navigating by themselves. An even worse case could be that the users face dangers due to malicious visualization. This is similar to the misleading effects of map scale on geometry and feature selection (Monmonier 2005).

1.2. Geovisualization and spatial learning

Geovisualization styles influence individuals' behavior and spatial learning as reported by Fuest et al. (2021), and the functions of visual variables perform differently in 2-Dimensional (2D), 3-Dimensional (3D) and immersive environment. User studies show that types of symbols significantly influence tourists' decisions on which place to visit when using a tourist map (Medynska-Gulij 2003) and visualization styles influence map-assisted spatial learning of expert wayfinders in outdoor navigation (Kapaj, Lanini-Maggi, and Fabrikant 2021). This might be related to the allocation of visual attention. For example, mobile map users with realistic-looking 3D landmarks share their visual attention more equally on task-relevant information, while those with 2D landmarks switch their attention between the visualized landmarks and the mobile map when performing navigation tasks (Kapaj, Lanini-Maggi, and Fabrikant 2021). Understanding how visualization influences users' behavior and spatial learning improves user experience during navigation.

Spatial learning is important during navigation (Huang, Schmidt, and Gartner 2012; Ruginski et al. 2019). When users have access to navigation aids, they usually do not intentionally learn the walked space, which degrades spatial learning and spatial ability to some extent. This has led to many concerns e.g., safety concern, from researchers, police and the public (McCullough and Collins 2019). The good news is that spatial learning also happens incidentally (Wenczel, Hepperle, and Stülpnagel 2017). Many studies show that users can perform secondary tasks while walking (McKendrick et al. 2016) and incidental spatial learning is possible (Wunderlich, Grieger, and Gramann 2022). However, if users are too concentrated on the main task, i.e., the navigation, the aforementioned inattentional blindness may occur and incidental spatial learning is less likely to happen.

Many of current findings for MR navigation are from using VR technologies instead of MR. VR environment is sometimes used to overcome the limitation with the FOV in MR Head-Mounted Devices (HMD). For example, Tran and Parker (2020) created a VR city and then added "virtual" elements to test the usability of up front, on street and on hand maps in hm-MR navigation. While it indeed provided a larger, human-like FOV, new concerns, such as motion sickness using joysticks to navigate, necessity to set slower walking pace, occur. Besides, many visualization ideas of current MR interface design originate from desktop or HMD VR games. Such games are mainly in or mimics a first-person view and the gamers need to remember the maps, which is important in spatial learning. However, in VR games, players do not have to switch their attention between the real and the virtual objects. For design of MR, Grasset et al. (2021) summarized the visualizations in MR and suggested that in MR the labels should not overlap with Point of Interests (POIs) or edges, and the contrast between video content and labels should be improved. However, those are neither specifically designed for hm-MR nor for navigation purposes. It remains to be explored, whether the provided visualizations satisfy the needs of MR navigation users, support the spatial learning and create pleasant navigation experience.

Direction indicators are an essential element for navigation. The orientation function of landmarks was previously underestimated, but is increasingly promoted by researchers and should be appropriately integrated into navigation aids (Fellner, Huang, and Gartner 2017; Lanini-Maggi, Ruginski, and Fabrikant 2021; Ohm, Ludwig, and Gerstmeier 2015). Currently there is no clear guideline of the visualizations of direction and landmarks for MR-based navigation. Arrows or other separate holograms are commonly used as direction indicators in current MR-based navigation apps, such as mobidev (Figure 2(a), MobiDev 2018), Dent Reality (Figure 2(b), Dent Reality 2019), Google Map Live View (Figure 2(c), Google Maps 2020), and Phiar (Figure 2(d), Phiar 2022). Sometimes arrows are also combined with lines to highlight the direction or turn (Figure 2(e), Phiar 2022). Another visualization, which may be more entertaining, is animated avatar (Figure 2(f), VIEWAR Augmented Reality 2020).

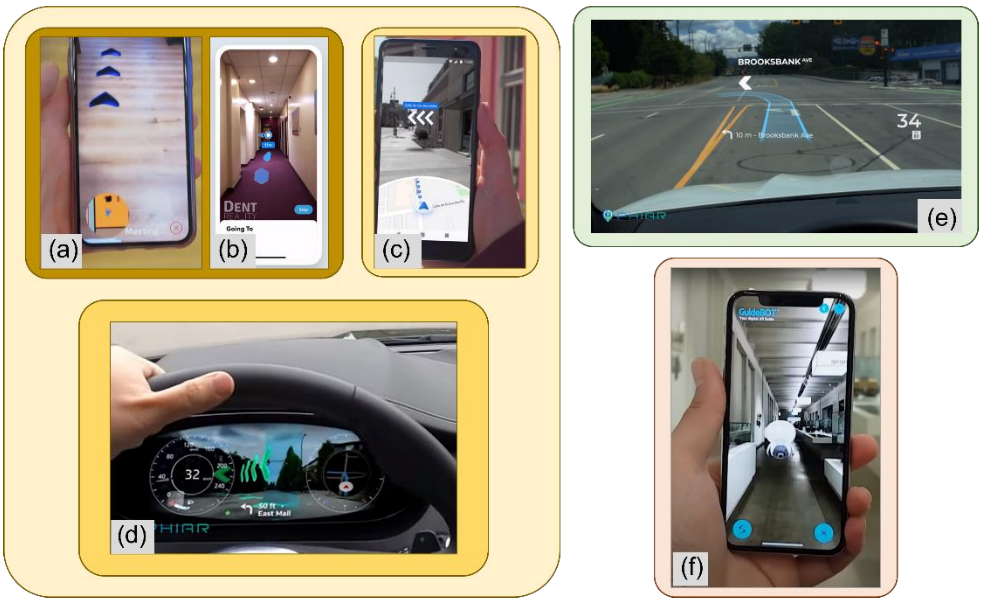


Figure 2. Typical visualization styles of direction. (a)-(d) separate arrows/dots, (e) separate arrows with consecutive lines, (f) animated avatar.

The visualization of using separate holograms as direction indicator is in line with the Gestalt principle of continuity, which means that elements that are arranged on a line or a curve are perceived to be more related (UserTesting 2022). Users should be able to perceive the separate arrows/dots as a continuous path. In fact, such visualization works well for navigation, i.e., simply reaching the destination. Previous researches have also confirmed that arrows are intuitive direction symbols (Liu, Ding, and Meng 2021). It requires only a small part of the limited FOV and thus spare much space for other information. Project-based MR found that the on-the-road arrows draw users' attention to the physical world (Knierim et al. 2018). However, it is not clear if such visualization requires more mental efforts than a consecutive line.

Landmarks are valued in navigation and spatial learning. As visually, semantically or structurally salient objects (Raubal and Winter 2002; Sorrows and Hirtle 1999), they proved to be useful and intuitive in navigation (Bauer, Ullmann, and Ludwig 2015; Bolton, Burnett, and Large 2015; Çöltekin et al. 2020; Dong et al. 2020; Wenczel, Hepperle, and Stülpnagel 2017). Li et al. (2014) found that visualizing distant landmarks supports users with low Sense of Direction (SOD) with spatial orientation. Credé et al. (2020) confirmed the advantage of globally visible landmarks improving survey knowledge acquisition. Landmark knowledge are acquired at the very beginning of spatial learning (Ishikawa and Montello 2006) and is essential and possible for incidental spatial learning. Landmark learning is a common task for the evaluation of spatial learning (Hedge, Weaver, and Schnall 2017; van Wermeskerken et al. 2016). When overloaded by the main task, one's visual field is narrowed (Kishishita et al. 2014) and the incidental learning of landmarks might be more difficult. During navigation, landmark learning is a secondary task and is also suitable for assessing mental workload of the main task, i.e., navigation (McKendrick et al. 2016).

1.3. Hypotheses in this study

To address the aforementioned cognitive issues associated with the interface design of hm-MR-based navigation, this study investigates the influences of different visualization styles on users' perception of the real world. We formulate two research hypotheses about hm-MR-based navigation:

Hypothesis 1: Incorrect virtual information misleads users' perception of the physical environment and lead to wrong spatial memory.

Hypothesis 2: Aligned separate holograms as direction indicator are perceived as a continuous path without additional mental efforts and do not influence spatial learning.

To test these two hypotheses, we built a MR-based navigation interface and conducted a user study where users performed tasks with the navigation aid. To test H1, we visualize an incorrect virtual path that conflicts with the physical environment. More specifically, we designed an artificial turn in a straight corridor. If users tend to remember the virtual path instead of the real environment, then H1 is true. To test H2, two visualizations are adopted for direction indicator, i.e., arrows with lines and without lines. We also visualize some of the semantic and structural landmarks of the study area. Mental effort is evaluated by standard questionnaires (see *2.5 Procedures*) and spatial learning is evaluated by learning of landmarks. Therefore, if the results of the questionnaire results and landmark learning remain the same for both with-line and without-line styles, then H2 is true. Otherwise, H2 is false. Furthermore, we collected user opinions about the interface design for future improvement.

2. User study

In this study, we design a navigation interface using Microsoft HoloLens 2 and conduct a user study. An artificial turn was introduced to test H1, two visualizations of direction indicators are used and selected landmarks are visualized to test H2. During the user study, the participants first conduct a pre-walking questionnaire including information of their knowledge background and SOD, and then use the navigation tool to reach the destination. A Post-walking questionnaire is used to assess mental workload and sketch maps are used to assess the spatial learning results. Finally, we interview the participants on their opinions about MR navigation and interface design.

2.1. Navigation interface design

The designed interface mainly consists of arrows with/without lines to show the direction, and semantic and structural landmarks. The participants are then randomly divided into two groups, i.e., the With Line (WL) group and the No Line (NL) group.

Three categories of landmarks are selected, i.e., elevator/lift, corridor/hall and administration office. We used pictorial symbols to represent the landmarks. Pictorial symbols are demonstrated more effective than geometric symbols (Halik and Medyńska-Gulij 2017), and thus may be more effective in unintentional perception. The symbols should be designed big enough to show the details. We use black and white symbols with thicker lines and straight shapes to make them easier to distinguish (Halik and Medyńska-Gulij 2017) and to avoid distracting participants from perceiving the physical world (Figure 3). We created these symbols from icons by vectorpocket, upklyak, pch.vector in freepik (www.freepik.com). They were rotated around vertical axis to keep facing the user.

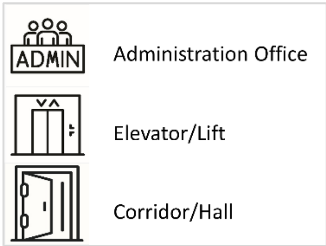


Figure 3. Pictures used in the interface design.

2.2. Participants

This user study recruited forty volunteer participants through posters online and around the university campus. All participants are adults (22 - 49 years old, mean age = 29.4 years old, SD =6.4 years old). Seventeen participants are female and 23 are male. According to the questionnaire in the user study, the participants have only limited experience with both AR and VR. None of the participants reported or was observed visual impairment.

2.3. Hardware and interface

We used Microsoft HoloLens (2nd generation, https://www.microsoft.com/en-us/hololens/hardware) in the user study. The device is with 2k 3:2 light engines resolution, >2.5k radiants holographic density and real-time eye tracking.

The interface is designed using Unity (https://unity.com/). For the two groups of WL and NL, the landmarks and arrows are identical, the only difference is that the lines are only shown in the WL group (Figure 4).

We first used Azure Spatial Anchor to save each hologram (e.g., each arrow was an independent spatial anchor). However, in a pilot study we found the loading of holograms is not ideal due to unstable internet connection and the participants were confused during the navigation. Therefore, we saved the whole path as one single anchor to make sure all the holograms are rendered in time. The visibility was set to 5 m.

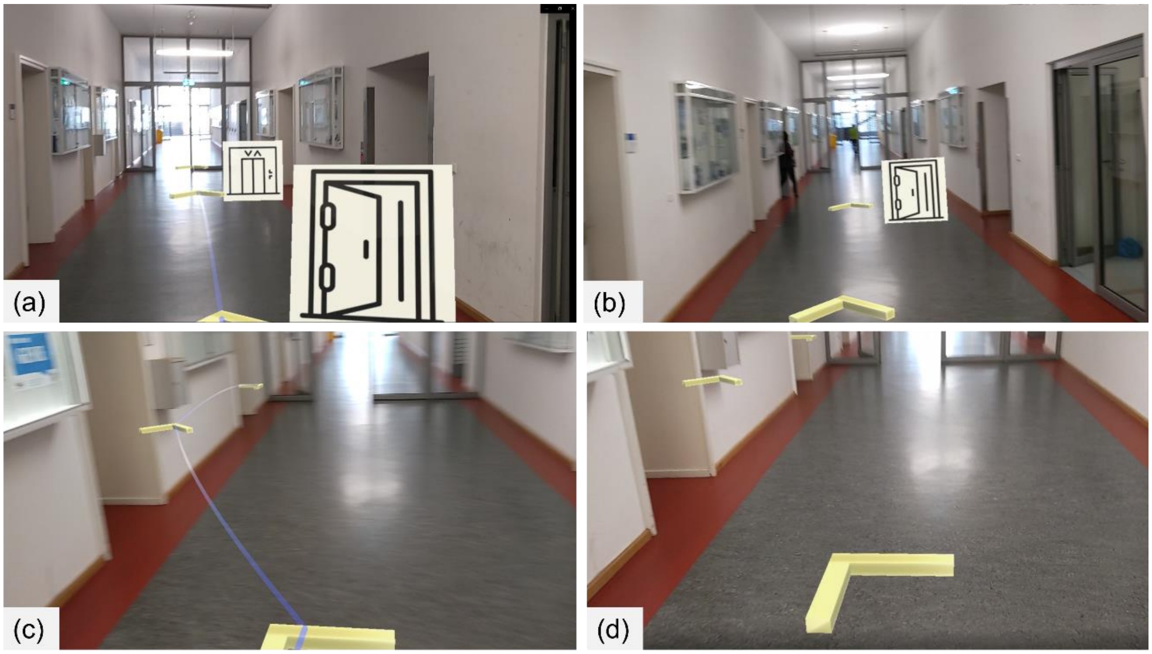


Figure 4. Participants' view at the start point, (a) WL group; (b) NL group, and before the artificial turn, (c) WL group, (d) NL group.

2.4. Study area

The user study is conducted in the main building at the city campus of Technical University of Munich (TUM). The study area is chosen for three reasons: (1) there are no windows, to keep a constant lighting condition; (2) there is more than one corridor along the path, to test participants' perception of both visualized and non-visualized landmarks; and (3) the walked path is wide enough to allow an artificial turn (Figure 4(a) and Figure 4(b)). The study area is shown in Figure 5.

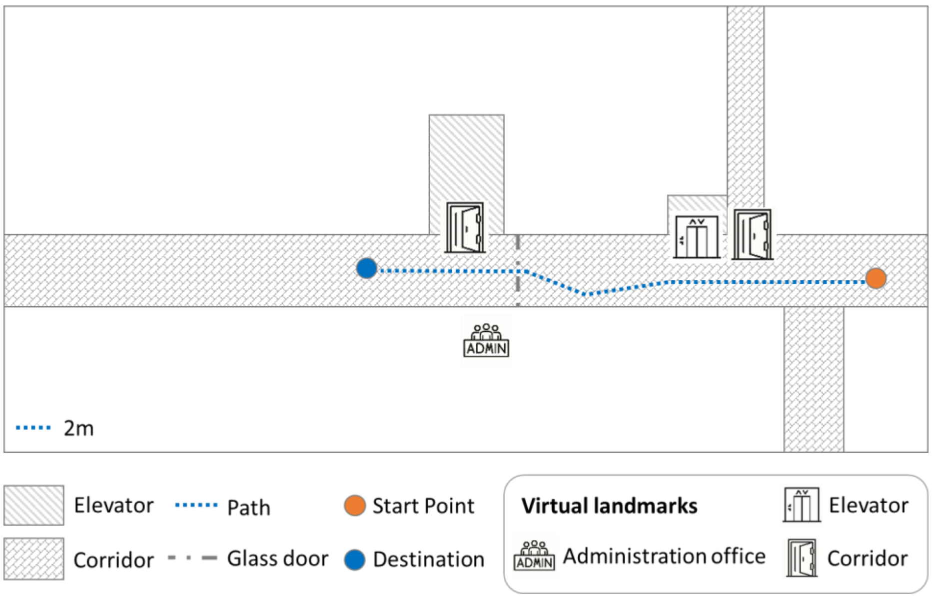


Figure 5. Study area in the user study, within TUM city campus.

2.5. Procedures

The main procedure of the user study includes a pre-questionnaire, a walking session, a post-walking-questionnaire, and a semi-structured interview. First, the participants were given the Informed Consent Form, which introduces the study briefly and informs them that they are free to quit the study at any time or withdraw their personal data. After signing the form, the participants need to do a pre-walking questionnaire. The pre-walking questionnaire includes personal information, Santa Barbara Sense of Direction Scale (SBSOD, Q1-Q15), which is widely used to assess SOD (Hegarty et al. 2002), if they get lost more easily indoor than outdoor (Q16), familiarity of AR and VR (Q17-Q18) and the Pre-state questionnaires of Short Stress State Questionnaire (SSSQ, Helton and Näswall 2015). Table 1 lists the questionnaire examples of Q16 - Q18.

Table 1. Questions 16–18 in the Questionnaire.

Question	**Circle the number indicating your level of agreement with the statement.**								
Q16. I usually get lost more easily indoor than outdoor.	Strongly agree	1	2	3	4	5	6	7	Strongly disagree
Q17. I have __ experience with Augmented Reality.	None	1	2	3	4	5	6	7	A lot of
Q18. I have __ experience with Virtual Reality.	None	1	2	3	4	5	6	7	A lot of

The task description informed the participants that they will be asked questions about the path after the walking. But the participants were not informed about the specific questions. During the walking session, the participants first needed to adjust eye position using HoloLens 2, then were shown the "legend" with examples of the elevator/lift, corridor/hall and administration office landmarks. The participants could read the landmark legends without time limit till they fully understood the meaning of the symbols. Afterwards they started the navigation part. After reaching the destination, the participants went back along the same corridor wearing the HoloLens 2 (without any instructions displayed) accompanied by the experiment designer. During the return trip, the experiment designer explained the following steps (e.g., the coming interview) to the participant and kept her/him focused on the conversation and distracted from remembering the environment.

For the post-walking questionnaires, the participants first need to draw a sketch map and answer related questions, then fill the post-state SSSQ (Helton and Näswall 2015), NASA Task Load Index (TLX)[2] questionnaire, answer questions about interface design and draw their own design of the interface. At last, there was a semi-structured interview based on the answers and the conversation was recorded.

The misleading effect of artificial turn is evaluated by asking the participants to judge the structure of the study area (Figure 6). This question is behind the sketch map task to prevent the options' influence. The question is: *Which of the following pictures is most similar to your impression of the structure of the study area?* As shown in Figure 6, we give 6 diagrams to show different structures, including straight line with no corridor (*A*), one corridor at the right side (*B*) and two corridors at both sides (*C*), and curved line with no corridor (*D*), one corridor at the right side (*E*) and two corridors at both sides (*F*). The correct answer is *C*, i.e., there are corridors on both side near the start point. Each of the options represents the participant's impression of the study area. For example, if a participant chose *B*, it means this participant was not misled by the artificial turn and remembered the physical environment correctly, and the participant remembered the corridor labelled by the virtual landmark but overlooked the not-labelled one.

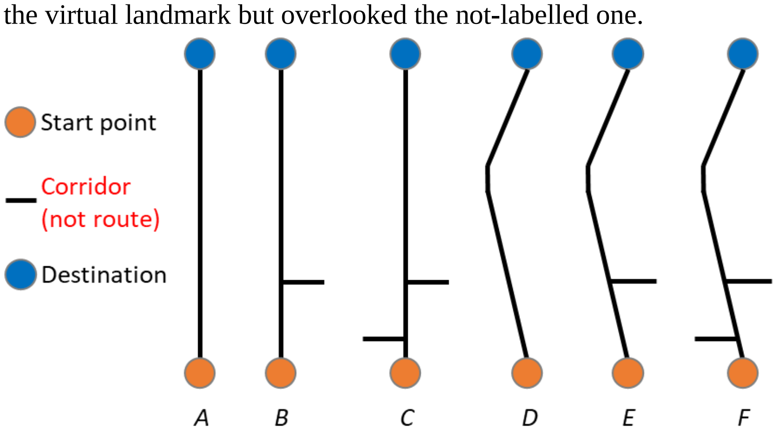


Figure 6. Six proposed options representing the study area structure.

3. Results

We analyzed the participants' pre-walking questionnaires, sketch maps and collected their opinions about the MR navigation interface design in the post-walking sessions. The post-state SSSQ and TLX questionnaires

[2] The NASA TLX Tool: Task Load. 2022. "TLX @ NASA Ames - Home." Accessed August 18, 2022. https://humansystems.arc.nasa.gov/groups/tlx/index.php.

were filled after the sketch mapping. The interview revealed that the participants filled the two questionnaires mainly based on the sketch map tasks instead of the navigation experience. They made great efforts to recall the route and found the tasks mentally demanding. Thus, the differences of pre-/post-state SSSQ and the results of the TLX questionnaire are mainly from the post-walking questionnaires instead of the navigation experience, which is beyond the focus of this study. Therefore, those results are not analyzed and reported in this paper.

3.1. Data analysis

3.1.1 Pre-walking questionnaire

The pre-walking questionnaire aims to reflect the participants' sense of direction, whether they get lost indoor more easily than outdoor, and their experience with AR and VR. The results are shown in Table 2. The SBSOD is 4.39 for the WL group and 4.52 for the NL group. The score for Q16 is 4.55 for the WL group and 4.26 for the NL group, which indicates that participants are more likely to get lost indoors. The score of Q17 and Q18 for both WL and NL groups are between 2 and 3, indicating that the participants have only limited experience with both AR and VR. A simple t-test is conducted to test the significance of the differences between group WL and group NL, and the participants show no significant differences in all four aspects (*p* values are all above 0.05). This indicates that the potential differences in data analysis results are not due to participants' differences, but are caused by the visualizations.

Table 2. Pre-walking questionnaire results (values represent: mean±standard deviation).

	SBSOD	*indoor*_lost	*VR Experience*	*AR Experience*
WL	4.39±1.52	4.55±1.57	2.60±1.73	2.55±1.73
NL	4.52±1.17	4.26±2.02	2.95±2.01	2.11±1.82
t	−0.289	0.496	−0.579	0.782
p	0.774	0.623	0.566	0.439
* $p<0.05$, ** $p<0.01$				

3.1.2 Sketch map

Right after the walking session, every participant was asked to draw a sketch map reflecting their memory of the walked area. Table 3 shows the results of sketch mapping. The general results of the WL group and the NL group are very similar. We counted how many participants remembered each of the elements. The largest differences between the WL and NL groups are the elements counting of corridor and correct direction, which are both four. But only two participants in the WL group drew the unlabeled corridor and participants from the WL group labeled more landmarks in most categories than those from the NL group. Regarding the pure real, physical objects (i.e., stairs, glass doors, and mailboxes), seven participants drew the short stairs near the start point, among which three are from the WL group and four the NL group. Twenty-seven participants drew at least one glass door with 14 and 13 participants from the WL group and the NL group, respectively. Among them, one participant in the WL group and two participants in the NL group drew two glass doors along the path, resulting in 15 glass doors in each group (see "Glass Door" in Table 3). One participant in the WL group remembered the mailbox near the turn. Concerning the objects labeled by virtual landmarks (i.e., elevators, administrative offices, corridors, and artificial turn), 34 participants drew the elevator with 18 participants are from the WL group and 16 NL group. The numbers of admin office drawn are the same as that of the elevator. More participants (17) drew the corridor from the WL group than that (13) from the NL group. Most of the participants (37) drew the artificial turn with 19 from the WL group and 18 from the NL group. Furthermore, among each group drawing this artificial turn, 12 participants from the WL group and 16 from the NL group drew the turn direction correctly.

Overall, more participants from the WL group draw the landmarks on their sketch maps. More of them draw correct numbers of the landmarks. Among all the participants, only one WL participant remembered the physical mailbox. However, more participants from the NL group remembered the direction correctly.

Table 3. The number of each type of object drawn on sketch maps.

	Stairs*	Glass Door		Mailbox	Elevator		Admin Office		Corridor		Artificial Turn	Correct Direction
		Users	Count		Users	Count	Users	Count	Users	Count		
WL	3	14	15	1	18	21	18	20	17	25	19	12
NL	4	13	15		16	20	16	16	13	21	18	16
Total	7	27	30	1	34	41	34	36	30	46	37	28

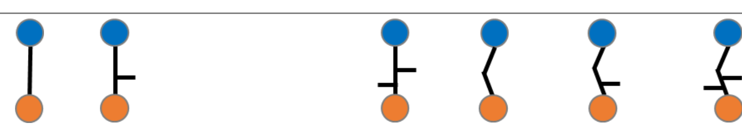
*For Stairs, Mailbox, Artificial Turn and Correct Direction: Users = Count

Directly after the sketch mapping, the participants scaled their self-confidence of their sketch. They were further asked to explain which part they are more confident of and why. For the confidence of sketch mapping, twenty-five participants' self-confidence is more related to category. For example, they may be more confident of the direction, and less confident about landmarks. Eleven of them also mentioned position-related confidence. For example, they are less confident about the order of landmarks or the last landmarks. Seven participants' confidence is only related to position, they are more confident about the things before the turn or the glass door, and less confident about those after it.

The results indicate that the artificial turn misled participants to some extent. The correctness of each option on the structure of the study area is shown in Table 4. Most participants chose *B*, i.e., only a corridor at the right side. Seven participants chose no corridor (*A*) and seven other participants chose the correct option *C*. These participants all remember the walked corridor as straight. Only two participants from the NL group chose *E*, where there was a turn in the walked corridor.

All the participants from the WL group remembered the path correctly, while 18 participants from the NL group did so (*A*+*B*+*C*). Seventeen and 16 participants from the WL and the NL groups remembered the labeled corridor (*B*+*C*+*E*+*F*). 16 participants in both WL and NL groups overlooked the physical unlabeled corridor (*A*+*B*+*D*+*E*) and another one participant in the NL group was not sure about this corridor. In general, the memorized study area layout of participants from both groups are quite similar. Only without lines, two participants were confused by the artificial turn (i.e., the conflicted virtual and physical information), and they remembered the physical layout with a turn.

Table 4. Results of study area structure question.



Structure Option		***A***	***B***	***B/C****	***C***	***D***	***E***	***F***
Correctness	Physical environment	+	+	+	+	—	—	—
	Virtual landmark	—	+	+	+	—	+	+
	Physical landmark	—	—	+	+	—	—	+
Group	WL	3	13		4			
	NL	4	10	1	3		2	

Total	7	23	1	7	2

*One participant in NL could not decide if it was *B* or *C*

3.1.3 *Interface design ratings*

In the questions about interface design, the participants were asked to evaluate the elements in the interface (arrows, lines and landmarks) from two aspects: (1) satisfaction, i.e., how participants like it, and (2) usability, i.e., how participants think it helps them remember the route. It was rated based on the 7-Likert-scale (1 not at all - 7 very much). The results are shown in Figure 7 and Table 5. In general, participants like the three elements we designed and regard them as useful, as all the values are above 4. For landmarks, the satisfaction and usability both tend to be higher in the WL group.

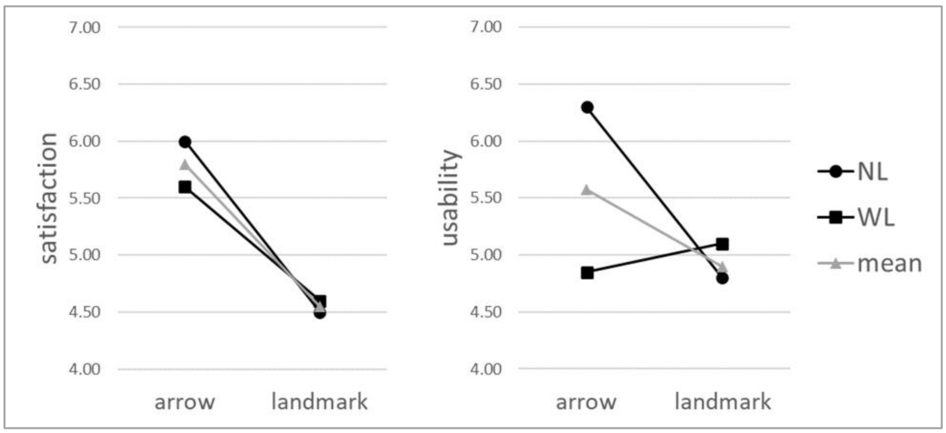


Figure 7. Satisfaction and usability rating results of the elements.

In the WL group, the line is liked most, followed by the arrow and the landmark. The usability of line is also the highest, and arrow is the least useful. In the NL group, both satisfaction and usability of arrow are higher than those of landmark. In both WL and NL groups, the satisfaction of direction indicators is higher than that of landmarks.

The satisfaction and usability of each element between WL and NL group are compared using two-way ANOVA and the results are shown in Table 5. The main effect of the element on the satisfaction is significant (p=0.001, p<0.01). The participants' satisfaction of arrow (5.80±1.38) is higher than that of landmark (4.55±1.74).

Table 5. Descriptive and ANOVA results for interface design ratings.

		Descriptive				ANOVA		
Group	element	WL	NL	*mean*		group	element	group*element
Satisfaction	line	5.75±1.48	—					
	arrow	5.60±1.64	6.00±1.08	5.80±1.38	*F*	0.179	12.461	0.498
	landmark	4.60±1.70	4.50±1.82	4.55±1.74	*p*	0.673	0.001**	0.482
Usability	line	5.20±1.64						
	arrow	4.85±1.73	6.30±1.49	5.58±1.75	*F*	1.935	2.286	4.480
	landmark	5.10±1.94	4.80±2.17	4.90±2.04	*p*	0.168	0.135	0.038*

* p<0.05, ** p<0.01

The interaction effect between group and element influences the difference on element usability rating

(p=0.038, p<0.05). A simple effects test was conducted to determine which factor was effective at each level. The results show that the element has significant influence on the usability rating in NL group. Without line, the arrow is regarded significantly more useful than landmark (*df*(arrow-landmark) =1.5). With line, the impact is not significant (p=0.670, p>0.05). Visualization group has significant influence on the usability rating of arrows. With line, the arrow's usability is significantly lower (*df*(NL-WL) =1.45).

Table 6. Simple effects test for usability (df: difference, SE: standard error).

	element	*df*	*SE*	*t*	*p*
NL	arrow - landmark	1.50	0.585	2.566	0.012*
WL	arrow - landmark	−0.25	0.585	−0.428	0.670
	group	*df*	*SE*	*t*	*p*
arrow	NL - WL	1.45	0.585	2.480	0.015*
landmark	NL - WL	−0.30	0.585	−0.513	0.609
				* p<0.05 ** p<0.01	

3.1.4 Post interview

Finally, we analyzed the answers to the open questions about interface design (Table 7). Among all the aspects, map is the most frequently mentioned element. Thirteen participants (five from the WL group and eight from the NL group) said they would like to have an overview map at the corner similar to that in games.

Interactive menus are also mentioned quite often (by 11 participants). The participants would like the menu to be either independent/call-out or based on clickable landmarks. Remaining distance or time to the destination is mentioned by eight participants (five from the WL group and three from the NL group), two participants were in favor of displaying the device status, as they felt that this would keep participants informed about current situation, such as whether the device functions normally and is reliable. Four participants would like to have avatars leading the way, but some of them prefer real-person sized virtual person while others prefer cats/dogs. Two participants would have cardinal directions, even with indoor navigation, as some buildings may use "North Gate". Two participants mentioned they would learn better with audio assistance.

Despite the joy of using MR, 11 participants expressed their concern for safety and one for workload. Some did not want any more information to be displayed, as the current settings are sufficient to guide the way without occluding the real world. Others emphasized the expectation of HoloLens giving danger warnings, such as of accidents, or just inflate floors. Seven participants would like to have more digitalized objects, but also combined with the real world, e.g., use doodles to represent/highlight the trees. Four participants said the landmarks should be closer to the real objects or to be linked with them by virtual lines. For the landmark design, the preferences are quite diverse, which indicates the necessity to provide participants with different or personalized styles. Three participants reported that they were bothered by the height of virtual objects and would like them to be lower, preferably on the ground.

Table 7. Participants' interface design suggestions in semi-structured interview.

	Map	Menu / more info	Safety / real-time status	Distance / time	Digitalize	Avatar	Closer to real object	Height	Device status	Cardinal direction	Audio	Workload
WL	5	5	6	5	4	1	2	2		1		
NL	8	6	5	3	3	3	2	1	2	1	2	1

Sum	13	11	11	8	7	4	4	3	2	2	2	1

4. Discussion

In this study, we proposed two hypotheses, including H1: incorrect virtual information misleads users' perception of the physical environment and lead to wrong spatial memory; and H2: aligned separate holograms as direction indicator are perceived as a continuous path without additional mental efforts and do not influence spatial learning. We compared the participants' SBSOD, VR/MR experience and if they are more likely to get lost indoor than outdoor. No significant differences are found between the two user groups. Therefore, the revealed differences in the tasks are caused by the visualization.

4.1. Discussion on Hypothesis 1

To test H1, we designed an artificial turn in a straight corridor. Most participants (19 from the WL group and 18 from the NL group) remembered this turn in their sketch maps. Twelve from the WL group and 16 from the NL group remembered the turn direction correctly. Despite this artificial turn in the visualized path, most participants correctly recalled the walked corridor as straight. But two participants from NL group confused the visualized virtual path with the physical corridor. For most participants (95%, 38 out of 40) the physical information surpasses the virtual one in most cases. They were aware of the mismatch between the virtual and physical worlds and corrected the misinformation.

For the participants who remembered the walked corridor with a turn, possible explanations are that they had to pay much attention to the upcoming arrows, or they were trying to interpret the virtual landmarks and ignored the physical world. This constant alert to the upcoming virtual objects may contribute to the inattentional blindness found in previous studies and caused participants to overlook physical objects. In our study, only in certain cases (5%, 2 out of 40), the incorrect visualization led participants to wrong spatial memory. This finding reveals the possible misleading effect but is indeed not a strong support for H1. However, the current study area is restricted within a simple straight corridor, which is much more limited than the daily navigating area. We all experience that the longer we travel and the more complex the environment is, the more difficult it becomes to stay oriented. People's spatial memory also decreases as they navigate (Ekstrom and Isham 2017). Therefore, it is logical to assume that in longer paths or more complex environments, the misleading effect would be stronger. User studies for more realistic daily navigation shall be conducted to test H1. Besides, the results also suggest that this misleading effect is related to the visualization, as the misleading effect is only shown in the NL group. The graphic design of the navigation interface requires much attention.

4.2. Discussion on Hypothesis 2

For H2, we found a similar trend for the memory of landmarks in sketch maps in the two groups. We investigated how many participants remembered each landmark and found that the difference between the two groups is very small (the largest difference is 4). However, in general the participants from the WL group remembered more landmarks and information than those from the NL group. Differences concerning the subjective evaluation of the holograms are also found between the two groups. When lines are present, the arrows are seen as significantly less helpful. Since the WL and NL group participants show no differences in the background (as shown in the pre-walking questionnaire), the differences are caused by the visualization. The arrows are significantly less useful in the WL group than in the NL group, and within the WL group the arrow was also rated lower for both satisfaction and usability than the line. The results indicate that the line is sufficient to show the direction in the WL group. Without lines, the arrow is significantly more helpful than landmarks, while with lines, the landmark are rated as useful as the arrow. When only arrows are presented, the participants may tend to search for the next arrows which show the direction, and ignore the virtual landmarks and the physical world. With continuous lines, the participants were able to shift more attention from the direction indicators, to virtual landmarks or physical objects. Therefore, the participants tended to rate the landmark the same as the direction indicator and they add more landmarks on the sketch maps.

Our hypothesis H2 is false, as with the separated arrows, the participants' spatial learning tended to be worse within the simple study area. Participants' subjective feelings about the interface elements are also influenced.

Nonetheless, since the sketch mapping interferes with participants' evaluation of SSSQ and TLX questionnaires, and the mental effort is not sufficiently analyzed, it's not clear if it requires more mental efforts for the participants to perceive the separate holograms as a continuous path. The mental effort will be better evaluated using objective measurements, for example, eye movement data or electroencephalogram (EEG).

4.3. General discussion on interface design

In the analysis of H1, with only arrows, some participants were misled by the incorrect virtual information. In the analysis of H2, participants in the WL group found arrows much less helpful than those in the NL group, and they also found arrows less helpful than line as the direction indictor. Therefore, we recommend not to use arrows as direction indicator, but to include lines or use only lines instead. Thus, the participants are less likely to be misled by potential mistakes and they can focus more on the landmarks.

According to the semi-structured user interview, participants have their own preferences for the display and MR *per se* is not satisfying enough for the daily use. Although most participants only have limited experience with MR, they have strong opinions on what the interface should look like. Therefore, we need to take users' personal opinions and preferences into consideration when designing MR applications/software. We found that some of participants' advice can be combined with previous scientific findings and well-integrated in the interface design. For example, in our study, participants proposed to use distance-dependent visualization. An ideal way of distance-dependent visualization is the combination of size and transparency in point symbols on mobile MR maps (Halik and Medyńska-Gulij 2017). The personalized preferences shown by our participants might explain the contradictory findings based on former studies (Halik and Medyńska-Gulij 2017). With the new technology, users expect more individualized interfaces. Besides, many relevant contextual factors, such as environment, interest and tasks, also influence users' behavior and thus should be adapted to (Bartling et al. 2022). Grasset et al. (2012) proposed to let the designer specify high-level style. However, our study suggests that the users should be provided with adaptable interface, i.e., be able to actively design their own style in the MR applications.

Some of the participants' intuitive suggestions might be contradictory with previous design guidelines. Many participants mentioned that overview maps should be displayed. However, showing overview maps might hinder the FOV and thus needs to be carefully designed (Tran and Parker 2020). We note that fewer participants from the WL group mentioned maps than in the NL group. The lines may create a sense of consecution and help the participants build some survey knowledge about the study area, thus relieve the need for a map. Again, we suggest including lines instead of only arrows as direction indicators to resume users' incidental spatial learning.

While participants ask for more interactive functions, it remains a question if it is really necessary or how the interactions should be designed. Since Bartling et al. (2021) found that under time pressure, the participants performed worse with map-related tasks, especially with highly interactive tasks. They recommend that with time pressure, interactions should be minimized for users' benefits. Similar conclusion is drawn in the work of Brunye et al. (2017), that participants under time pressure rely more on egocentric information so as to avoid cognition overload. Therefore, it is not ideal to introduce too much information (Brunye et al. 2017). Such conclusions may not be drawn in different displays and may not be applicable in XR-based navigation. Nevertheless, these factors shall be considered in the MR-based navigation interface design. Our study shows that users' preferences for the MR-navigation interface are diverse, and some may be contradictory to academic findings. Further research should be conducted to improve our understanding of the cognitive issues in MR-based navigation, and to maximize the usage of MR in spatial learning. For example, to analyze *how* and *to which extent* the MR-based navigation interface should be adaptive/adaptable.

4.4. Limitations

The current work revealed the visualization's impact on spatial learning during MR-based navigation from descriptive results. Incorrect visualization could mislead users to wrong spatial memories, and the separated holograms as direction indicators tend to be more mentally demanding and make spatial learning more difficult. Further user studies with larger study areas and more participants are needed to testify to which extent the findings hold. Besides, objective measurements of mental workload, such as EEG and eye-tracking, are to be involved to investigating visualization's and other factors' (e.g., SOD) impact on spatial learning in detail.

5. Conclusion and future work

In this study, we proposed two hypotheses concerning the effects of visualization on spatial learning in head-mounted MR-based navigation. Specifically, we test whether incorrect virtual information can mislead users' perception of the physical world and whether using separate holograms as direction indicator increase mental efforts and influences spatial learning. We designed an indoor navigation interface, which visualizes semantic and structural landmarks using pictorial icons and the direction using arrows with/without lines. Based on this prototypical interface, we conducted a user study using Microsoft HoloLens 2 and collected user feedback about the interface design.

We found preliminary confirmation of the first hypothesis, i.e., incorrect visualization can mislead users and leave wrong spatial memories. Two participants remembered a straight corridor as with a turn. Luckily, it is not quite common and most of the participants remembered the walked area as a straight corridor correctly. The second hypothesis that separate holograms do not introduce more mental efforts is rejected by the user study results. The separate holograms seem to be more mentally demanding, as participants in the With Line group remembered more landmarks and more details, and they all remembered the physical corridor correctly. Still, more advanced methods of mental workload measurement (e.g., EEG and eye-tracking) should be involved to further investigate the impact on mental workload.

Our results show that the misleading effect can be overcome by including lines rather than using only arrows as direction indicator, which allows users to attend more to the physical world. Therefore, different from the current navigation applications which use arrows, we recommend including lines as direction indicator for better incidental spatial learning. In addition, the user feedback in this study shows that participants have their strong preferences for personalized visualization styles and interfaces. Tools with customized navigation interfaces to different users will benefit users' spatial learning and the usability of head-mounted MR-based navigation. We also call for a more in-depth investigation of head-mounted MR-based navigation interfaces in daily navigation situations and their impact on spatial learning, and for the development of adaptive and adaptable navigation.

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Data Availability Statement

The datasets generated and analyzed during the current study are not publicly available as they contain information that could compromise privacy and consent of research participants, but they are available from the corresponding author on reasonable request.

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Spatial Knowledge Acquisition with Virtual Semantic Landmarks in Mixed Reality-Based Indoor Navigation

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Abstract

Landmarks are essential and widely used in human navigation. However, many indoor environments lack visually salient landmarks, which leads to difficulties in navigating in and learning complex and similar-looking indoor environments. In this study, we designed and implemented virtual semantic landmarks in Mixed Reality (MR)-based indoor environments and conducted a user study to explore whether such landmarks can assist spatial knowledge acquisition during navigation. More specifically, we employed the untethered, head-mounted mixed reality device Microsoft HoloLens and used iconic holograms to show the semantic landmarks. In the user study, we used sketch map, landmark locating tasks and interview to assess the results of the spatial knowledge acquisition and collect advice on improving the MR-based navigation interface. The results show that virtual semantic landmarks can assist the acquisition of corresponding knowledge, as such landmarks were labeled second most often in landmark locating task. In addition, individual cases show that head-mounted mixed reality devices may influence not only vision, but also height or time perception of certain users. Our result can be applied to facilitate the design of MR-based navigation interfaces and assist spatial knowledge acquisition.

Keywords: Mixed reality, Indoor navigation, Virtual semantic landmark, Spatial knowledge acquisition

Introduction

According to the USA National Human Activity Pattern Survey conducted in 2001 (Klepeis et al. 2001), modern (American) people spend nearly 90% of their time in closed buildings. In the buildings, aside from staying at one place, people often need to move from one location to another, sometimes repeatedly. Therefore, it is important for people to navigate smoothly in a building and also learn about the indoor layout to facilitate their daily wayfinding activities.

Despite the high amount of time spent indoor, people still get lost more easily indoor than outdoor, especially in large and complex indoor environments such as those inside university buildings, hospitals, and airports (Bauer, Müller, and Ludwig 2016). Many factors influence indoor navigation, including the spatial structure of the building, the cognitive maps constructed during people's navigation and the individual strategies and the spatial ability of the people (Carlson et al. 2010). Indoor navigation aids can help overcome difficulties in wayfinding process. However, these aids are still limited, mainly due to the lack of stable penetration of global navigation satellite system (GNSS) signals and the low adopted indoor positioning systems (Chen and Clarke 2020). The emerging mixed reality (MR) technology provides new possibilities to indoor navigation. Self-contained MR devices can display virtual holograms and allow users to see the real world simultaneously, and they enable the spatial mapping without further hardware at a satisfactory accuracy (Munoz-Montoya et al. 2019). Moreover, nowadays the MR devices are becoming untethered and increasingly comfortable to use.

However, an overreliance on navigation aids can lead to decreased spatial knowledge acquisition of the way finders and damage their spatial ability in the long run (Ruginski et al. 2019; Gramann, Hoepner, and Karrer-Gauss 2017). Thus, many research works appeal for a balance between the usability of navigation aids and the spatial knowledge acquisition in navigation systems (Brügger, Richter, and Fabrikant 2019). Two possible solutions can facilitate spatial knowledge acquisition: active decision making (Wen et al. 2014; Brügger, Richter, and Fabrikant 2019; Farrell et al. 2003) and integrated landmarks in route description (Krukar, Anacta, and Schwering 2020; Duckham, Winter, and Robinson 2010). However, active decision making introduces extra workload, which may discourage users (Wen et al. 2014). Integrating landmarks, which are visually, structurally or semantically salient objects (Raubal & Winter, 2002), is not easy either for indoor navigation. Many indoor environments lack visually salient landmarks that can be used for efficient navigation. Besides, for the first-time visitors, structural (Golledge, Dougherty, and Bell 1993) and semantic landmarks are not easily recognizable. With the help of MR technology, it is possible to visualize or augment semantically salient landmarks to support indoor navigation in such cases. In this explorative study, we analyze whether these landmarks can assist spatial knowledge acquisition.

Before presenting our methods and results, we firstly introduce relevant background knowledge on MR and navigation, spatial knowledge acquisition and landmarks in navigation, and then give a brief explanation of our research question.

Mixed reality and navigation

The term *mixed reality* was first used to refer to all the areas between a real environment and a completely virtual environment in the reality-virtuality continuum, including augmented reality and augmented virtuality (Milgram and Kishino 1994). Today, such a blend of the real and virtual world is either called mixed reality (Microsoft 2020a; Rehman and Cao 2017; Guarese and Maciel 2019) or augmented reality (Google 2020; Faria, Gabbard, and Smith 2020; Rehman and Cao 2017) and an exact distinction is hardly possible. In this paper, we use the definition by Çöltekin et al. (2020), as "*MR suggests that there is real time spatial referencing (i.e., spatial computing), thus virtual and real objects are in the same spatial reference frame and meaningful interactions between them is possible, whereas* information *superimposed anywhere in the world (such a heads-up display, menu items etc.) would be AR*". Therefore, we use the term mixed reality (MR) to refer to the technology we use in this study although the term *augmented reality* was used in some of our cited studies.

MR is intuitive to use (Narzt et al. 2006; Rehman and Cao 2017) and has already been applied in a variety of aspects in people's life. Aside from the MR applications for mobile phones or tablets (Çöltekin et al. 2019), smart glasses that can be connected to smartphones via Bluetooth also give the wide audience an affordable option to use head-mounted MR. This untethered solution allows common users to benefit from MR-based navigation aids without having to hold their phone.

MR has long been used for navigation (Narzt et al. 2006). Even before the high-tech devices were introduced, researchers used virtual icons displayed on photos to conduct "MR"-based navigation (Hile et al. 2008). Although the hardware is quite different, superimposing virtual objects upon the real world is helpful for navigation. More recently, hand-held MR (Huang, Schmidt, and Gartner 2012; Chu, Wang, and Tseng 2017) and wearable device (Rehman and Cao 2017) have been used in navigation research with promising effects. Compared with hand-held MR, navigation with a wearable device is perceived to be more accurate and intuitive (Rehman and Cao 2017). Users can find their destinations faster with graphic landmarks in MR than with maps (Chu, Wang, and Tseng 2017). MR-based navigation also has advantage over well-established navigation tool as it requires less attention (Guarese and Maciel 2019).

However, similar to other mobile navigation aids, using MR for navigation may diminish users' self-navigation ability and cognitive issues need to be considered to optimize the navigation aids (Edler et al. 2019). Huang, Schmidt, and Gartner (2012) analyzed the results of landmark recognition, route direction and landmark placement tasks, and they found no significant difference in spatial knowledge acquisition from using mobile maps, MR or voice instruction – all these options yielded unsatisfactory results. Rehman and Cao (2017) compared the MR-based indoor navigation aid, both hand-held and head-mounted, with paper maps, and found that the former resulted in worse route retention. Therefore, they suggested design improvements to take both navigation and map memorization and retention into consideration.

Spatial knowledge acquisition and landmarks in navigation

Spatial knowledge, which reflects people's knowledge about the environment, includes landmark knowledge, route knowledge and survey knowledge (Ishikawa and Montello 2006), and is essential in forming people's navigation behavior (Cock et al. 2019). The easily accessible navigation aids nowadays can efficiently guide users to their destinations and are supposed to help the spatial knowledge acquisition as well. However, common users tend to ignore the idea to "learn" if they can simply follow the instructions without thinking, and they may have difficulties remembering the routes (Rehman and Cao 2017). Even worse, these navigation aids may damage spatial knowledge acquisition (Ruginski et al. 2019) and people's wayfinding ability in the long run (Gramann, Hoepner, and Karrer-Gauss 2017; McKinlay 2016). Apart from the scientific evidence, police also encourages the public, especially the hiking people, not to neglect their own wayfinding ability (BBC News 2020). Even young people who quickly adopt new technologies express their concerns about GNSS compromising navigation skills (McCullough and Collins 2019).

Spatial knowledge acquisition can take place both intentionally and incidentally. Some researchers believe users can only learn spatial knowledge by actively exploring or remembering the environment according to the active encoding principle (Brügger et al. 2019; Wen et al. 2014). However, the "extra" workload may prevent users from using such navigation systems. Other researchers found it possible to acquire spatial knowledge incidentally. Actually, incidental rather than intentional learning is the main difference between people with and without a good sense of direction (SOD) (Burte and Montello 2017). The study of Gramann, Hoepner, and Karrer-Gauss (2017) in a driving scenario proves that incidental spatial knowledge acquisition can be improved with modified navigation instructions.

Landmarks, which have been used for route description (Duckham, Winter, and Robinson 2010) and preferred by users (Ohm, Ludwig, and Gerstmeier 2015), also support spatial knowledge acquisition. Raubal and Winter (2002) identified landmarks as visually, structurally or semantically salient objects. These categories are widely accepted and considered in landmark salience evaluations (Lara, Antonio, and Peña 2018; Wang et al. 2020; Zhu et al. 2019). Landmarks are fundamental to spatial knowledge acquisition and landmarks knowledge is developed prior to route and survey knowledge (Duckham, Winter, and Robinson 2010). Although there is still debate about the importance of at-turn and straight-by landmarks (Wenczel, Hepperle, and Stülpnagel 2017; Fellner, Huang, and Gartner 2017), landmarks can doubtlessly serve as “anchor points” and support users’ self-localization (Bauer, Müller, and Ludwig 2016). Including landmarks in route instructions may help improve incidental learning in real walking scenarios (Wunderlich and Gramann 2019) and in driving simulator (Krukar, Anacta, and Schwering 2020). For virtual reality, the work of Cao, Lin, and Li (2019) on fire evacuation also suggests designers to use recognizable landmarks and increase their visibility.

Unfortunately, many indoor environments lack visually salient landmarks, which is one of the possible causes of getting lost indoor (Dubey et al. 2019). Public buildings can be complex (C. Wang et al. 2019) without sufficient visually salient landmarks. Some public buildings (or other indoor environments, e.g. in ships), such as universities, hospitals and hotels, have highly identical indoor environments. Rooms with special functions in such buildings, e.g., administration offices in universities, conference rooms in hospitals or laundry rooms in hotels, which might be relevant to most people and semantically salient, are visually similar to their neighbors. People get easily lost when they try to find their way in such indoor spaces, as they tend to search for visual instead of semantic landmarks in complex decision-making situations (Dong et al. 2020). This problem of the lacking landmarks may be relieved with the help of MR. For example, holograms can be used as *virtual semantic landmarks* to highlight such non-visual semantic landmarks.

However, more information associated with virtual semantic landmarks does not necessarily guarantee better learning results. Multimedia learning requires people to split their attention among multiple sources of information and then perform mental integration, which calls for more working memory and impairs learning (Ayres and Sweller 2005; Mayer and Moreno 1998). This *split attention effect* is not only between vision and auditory (Kalyuga, Chandler, and Sweller 2004), but also happens within vision, e.g. between pictorial and textual information (Mayer and Moreno 1998). Although virtual semantic landmarks are also visual information and shall merge with the real world, it is not known how users associate or switch their attention between them. The extra information introduced by MR mentioned in *Mixed reality and navigation* and the split attention effect may damage spatial knowledge acquisition (Gardony et al. 2013; Gardony, Brunyé, and Taylor 2015). A recent preliminary evidence from Dong et al. (2021) is that although users’ interaction intensity with 2D maps and hand-held MR navigation shows no significant difference, the users who navigated with MR navigation aid remember the route significantly worse. With the contradictory influence of virtually visual saliency versus split attention and extra workload, it is not clear if virtual semantic landmarks can assist spatial knowledge acquisition in MR-based indoor navigation.

We try to answer this question in this exploratory study. Our hypothesis is that virtual semantic landmarks in MR can assist spatial knowledge acquisition during indoor navigation. We designed a user interface for head-mounted MR-based navigation, combining turn-by-turn instructions with virtual semantic landmarks. We conducted a user study in a highly identical indoor environment to test our hypothesis.

Methods

In this work, we designed a MR-based navigation interface for HoloLens (see the section *Device*). The interface was improved iteratively after two preliminary user studies conducted in the same study area using the same device as the one used in this user study, and involving two and four participants respectively. The details of the preliminary studies are reported in Liu and Meng (2020).

Study Area

The study was conducted in the main campus of Technical University of Munich (TUM, Figure 1a, source: TUM (2020)). The whole route is about 120 m long, on the second floor and includes two turns (Figure 1b). This area is chosen mainly for three reasons: first, this part of the building has an identically looking indoor environment with white walls and grey doors (Figure 1c), is semantically rich, including administration offices, kitchens, stairs/elevators, seminar rooms, but includes limited visually salient landmarks, i.e. some pillars after the first turn. Second, regular visitors (mainly students and staff members) need to revisit it often as there are many seminar rooms and administration offices, and they need to be able to navigate by themselves. Third, there is no window along the route (except for a decorative, colorful window after the first turn). This almost sunlight-free and evenly lighted environment is ideal for the tracking performance of HoloLens (Microsoft 2020f), and thus perfect for the stable and accurate placement of holograms.

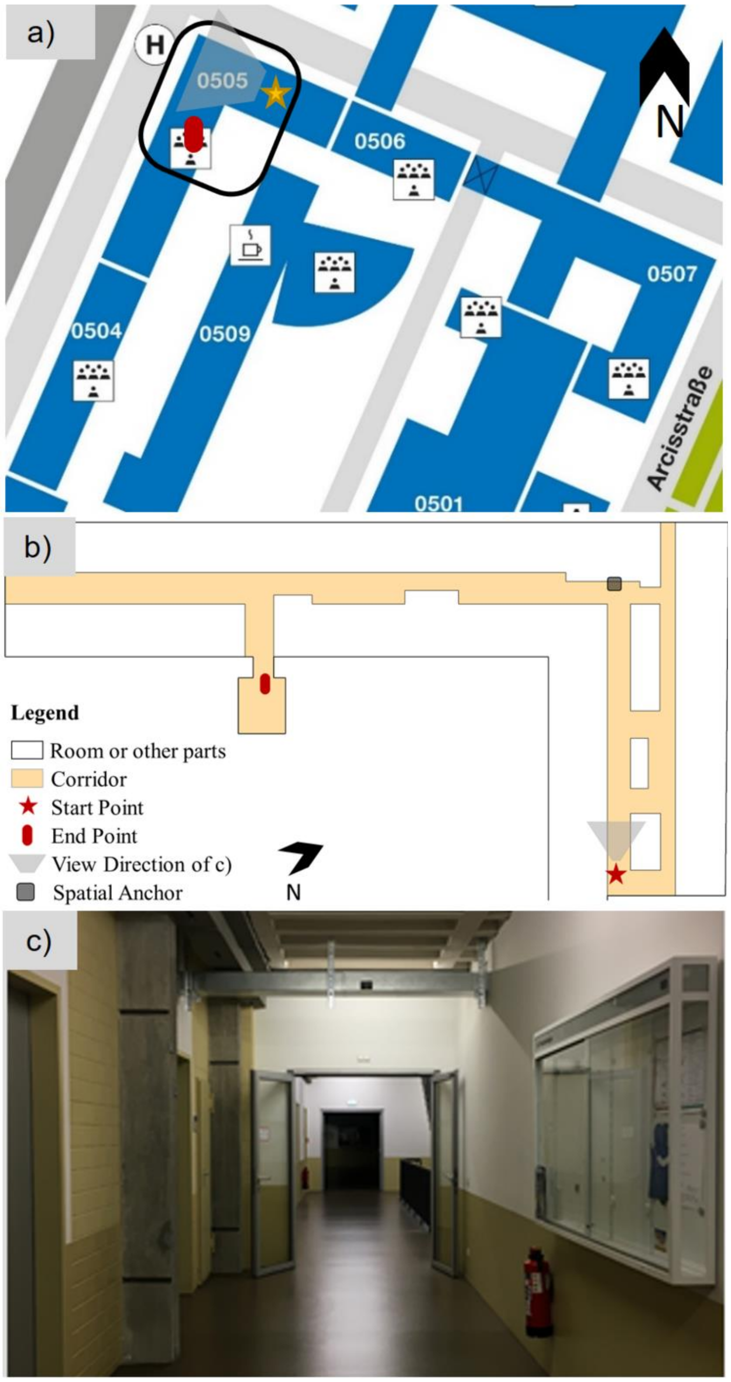

Figure 1 The study area. 1a) the location of the study area (within the red frame) in the building of the TUM main campus, source: TUM (2020); 1b) the (simplified) floorplan of the study area; 3) a snapshot of one corridor in the study area taken at the start point.

Participants

28 participants aged 21-48 years old (average = 29.6, SD = 5.8; 12 females and 16 males) took part in the user study. They were recruited via online or on-site ads, which were in English. All of them had been in Germany for more than 6 months. Their familiarity with MR or the study area was not taken into consideration in the

recruitment, but was asked during the study. All the participants signed the Informed Consent Form and were informed that they could retreat from the study at any time.

Device

In this study, we use the device Microsoft HoloLens (1st generation) with see-through holographic lenses and the weight of 579 g. It has 2 HD 16:9 light engines producing 2.3 M total light points concerning holographic resolution (Microsoft 2020d) and the estimated field of view is 30°×17.5° ("Microsoft HoloLens - Wikipedia" 2020). It is untethered, highly mobile and hands-free, thus suitable for navigation.

We used Microsoft Mixed Reality Toolkit (MRTK) v2 (Microsoft 2020e) to access the spatial awareness function and Unity (https://unity.com/) for the development of the application and interface.

Interface Design

In this interface, clipping planes are set to 0.85-5, as recommended by Microsoft (Microsoft 2020c). We designed step-by-step instructions using arrows to indicate the direction, and iconic holograms to indicate semantic landmarks. The arrows were arranged approximately 2 m away from each other along the straight route and closer before the turns, so that there were always 1-3 arrows in the view field of participants (Figure 2, the icon is designed by freepik from www.flaticon.com).

Figure 2 Participant's view in the see-through lens at the start point (the actual FOV is wider as the camera only covers part of the whole lens).

We used three iconic holograms as virtual landmarks for administration offices (Figure 3). These virtual landmarks were placed near the corresponding offices and rotated around vertical axis so the participants can always see the front of the virtual landmarks. The arrows were set at about 0.5 m above the ground. However, as a local spatial anchor instead of Azure Spatial Anchor (Microsoft 2020b) was used, the framework needed to be anchored each time when the system started. Therefore, the positions of the holographs were not exact the same for different participants. The spatial anchor was posited around the first turn (Figure 3, “Spatial Anchor”).

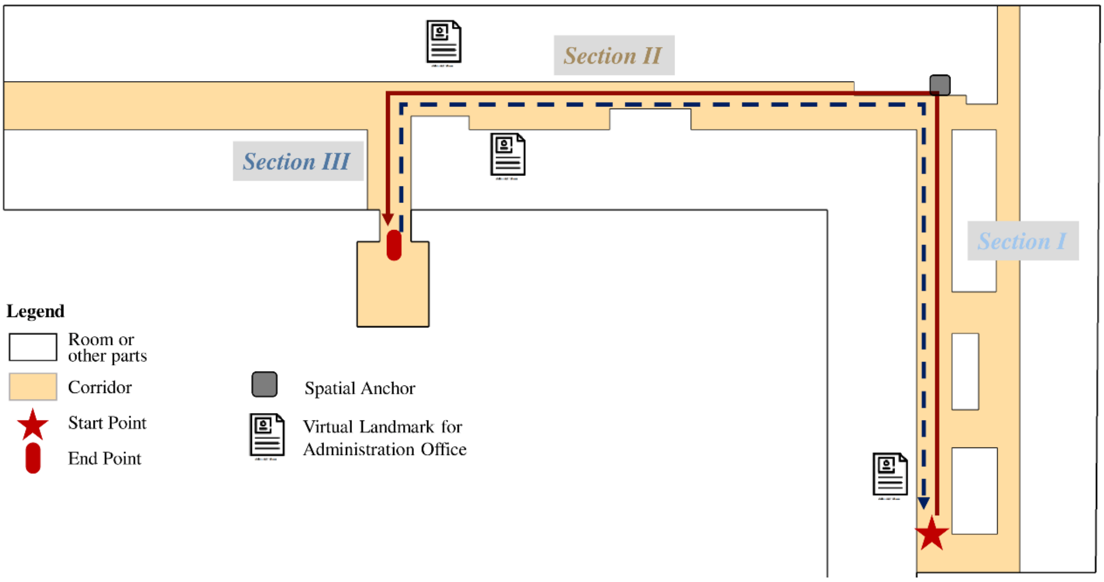

Figure 3 The overview of the experiment procedure (red line: walking to the end point wearing HoloLens; blue dotted line: returning to the start point independently). The two turns divided the whole route into 3 sections.

Procedure

In the user study, the participants first gave their demographic information, and then wore the HoloLens to reach the destination following the route displayed. The video-taking function of HoloLens was used to record what the participants saw during the walking. Afterwards, there was a task session including sketch mapping, questionnaire filling and landmark locating (Figure 4) tasks. For sketch mapping, the participants needed to draw a sketch map illustrating everything they remembered about the route on a blank piece of paper. Then, they filled in a questionnaire, which included SBSOD (Q1-Q15, Santa Barbara Sense of Direction Scale) (Hegarty et al. 2002) and questions on their prior knowledge about the study area, the MR/VR technology and general opinions on the walking experience (Q16-Q21, Table 1). Similar to SBSOD, Q16-Q21 also used seven-point scale measures (1: strongly agree - 7: strongly disagree). Participants were allowed to clarify with the experimenter the questions they found difficult to understand. In the landmark locating task, the participants then labeled landmarks they remembered on a given map (a simplified floorplan). This task shares some similarities with the “landmark placement task” in Huang, Schmidt, and Gartner (2012), but only with categories instead of specific landmarks. Then there was a semi-structured interview. Finally, the participants needed to go back to the start point independently.

We used both blank paper for sketch mapping and floorplan to encourage the participants to document other information about the route, as suggested by Rehman and Cao (2017).

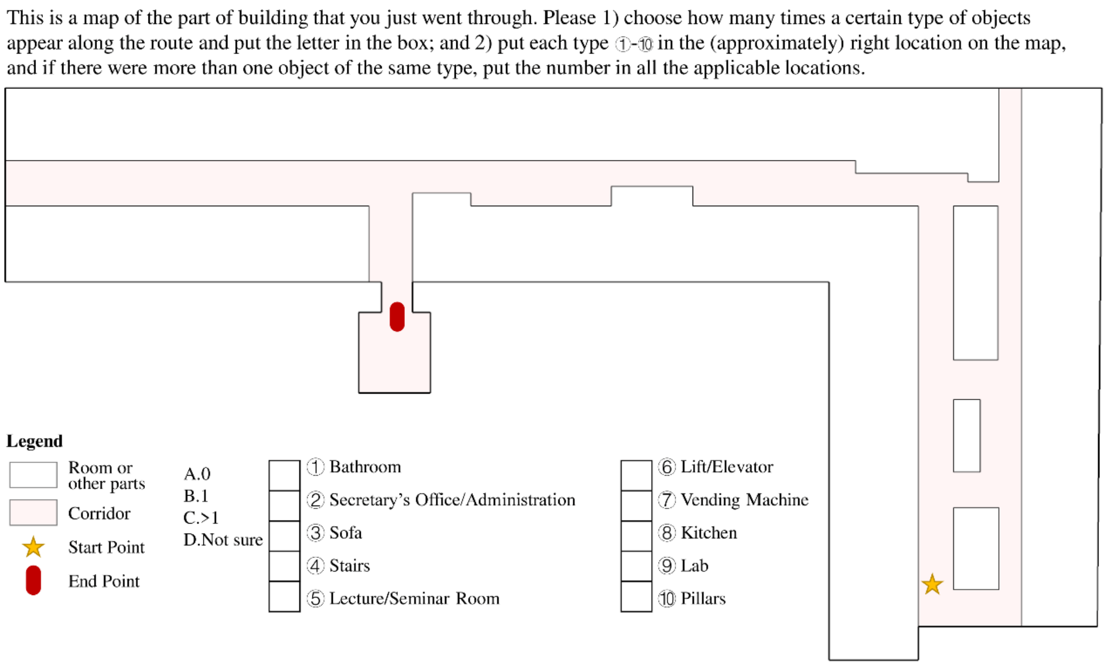

Figure 4. Material used in landmark locating task.

No.	Question (1: strongly agree – 7: strongly disagree)
Q16	I am very familiar with the study area.
Q17	I usually get lost more easily indoor than outdoor.
Q18	I have much experience with *Augmented Reality**.
Q19	I have much experience with Virtual Reality.
Q20	I like the hardware very much.
Q21	I like the interface very much.

***We use the term "mixed reality" in this paper.**

Table 1 Question 16-21 in the Questionnaire

Results

In this section, we report the results of the user study. We first look into the participants' background in the filled questionnaires, and then investigate the result of spatial knowledge acquisition derived from sketch maps and landmark locating tasks. Finally, we analyze the feedback from the interview and the recorded video clips from HoloLens. All participants reached the destination and went back to the start point without HoloLens successfully.

Questionnaire

The questionnaire results are shown in Figure 5. Q1-Q15 are grouped and reported as SBSOD scores, and Q16-Q21 are calculated and reported individually. The average SBSOD score of the participants is 4.038. The participants have a neutral self-report SOD. At the time this study was conducted, participants were not very familiar with the study area (Q16, 4.32, 17 participants gave a score equals to/larger than 4). They did not get lost more easily indoor than outdoor (Q17, 3.93), and they did not have much experience with MR (Q18, 5.57) or VR (Q19, 5.61). They were positive towards the hardware (Q20, 2.93) and the interface (Q21, 2.71).

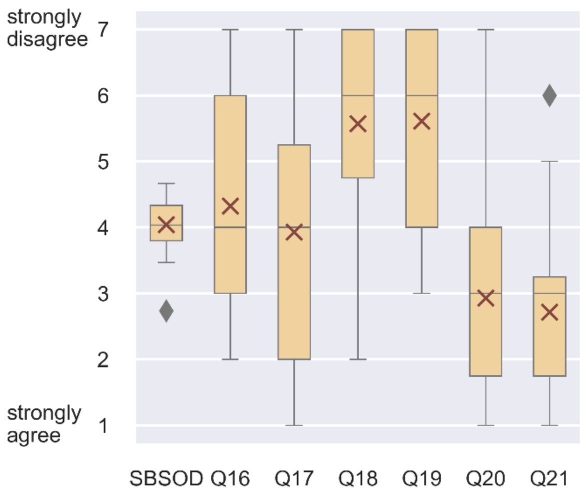

Figure 5 Questionnaire results, red x represents mean value.

Sketch Map

To assess the accuracy of the collected sketch maps, we use the number of the turns and the relative lengths of the 3 sections of the whole route (Section I, II and III, as shown in Figure 3). Participants get 1 point if they drew the double-left turns correctly and 1 point for each correct relative distance, i.e. Section I < Section II, Section I > Section III, and Section II > Section III. Therefore, the accuracy ranges between 0 and 4.

For the turns, 21 of the 28 participants remembered the directions correctly as double-left turns. The average score of the final accuracy is 2.43 for all the participants. Figure 6 shows the details of sketch map accuracy.

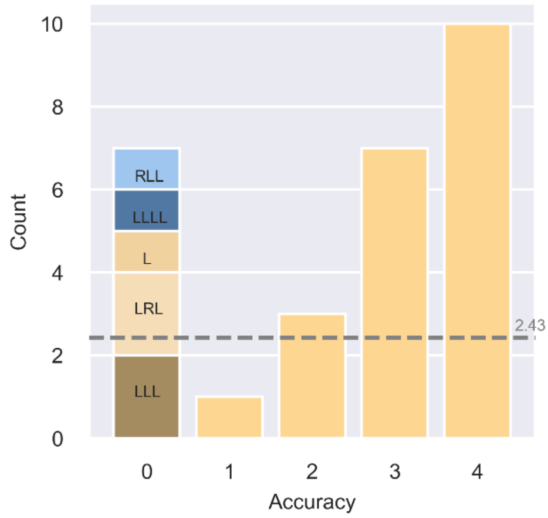

Figure 6 Sketch map accuracy. (Accuracy-0 shows the details about incorrectness of the participants remember the turns. L: left turn. R: right turn, e.g. RLL: the participant drew right-left-left turns.)

Landmark Locating

Table 2 illustrates the number of each kind of landmarks that were located by all participants in total. It shows that participants drew stairs most, followed by Administration Office and Lift/Elevator. Bathroom was labeled the fourth most.

Category	Count
Stairs	47
Administration Office	42
Lift / Elevator	36
Bathroom	25 (29*)
Lab	28
Lecture Room	19
Pillars	14
Kitchen	11
Sofa	3
Vending Machine	3

Table 2 Counts of landmarks labeled on the given map by all participants (* 29 bathrooms were placed originally. Two adjacent bathrooms were considered as one landmark as they probably refer to the adjoining male & female bathroom. Removing the duplicates, 25 were left).

For the correctness of landmark locating, only visually salient physical landmarks and landmarks labeled with virtual landmarks are considered in this analysis (Figure 7). Spatial knowledge acquisition usually results in a rough idea or a general layout about what is where instead of a precise map. Therefore, relative locations rather than metric information are used to assess the correctness of landmark locating.

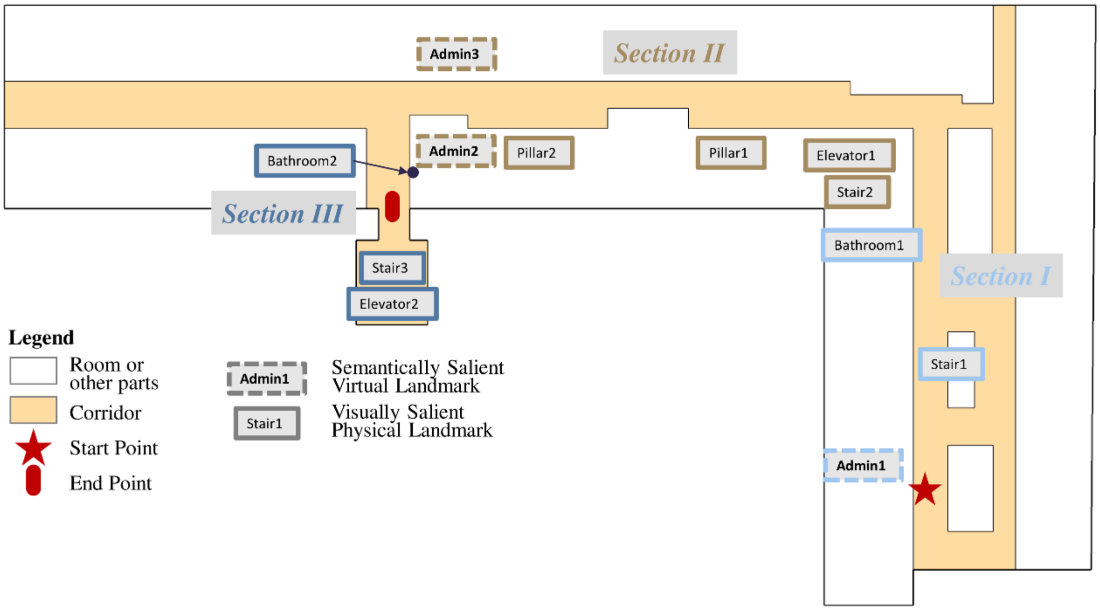

Figure 7 Landmarks considered in correctness analysis of landmark locating task.

A landmark is considered to be located at the correct position if it is 1) on the correct section of the route; 2) on the correct side of the corridor; and 3) at the correct part of the section or correctly located relative to another landmark (Figure 8a). Elevators at turn are considered as correct if put on the opposite side of the turn (Figure 8b). As Admin3 appears almost in the middle of view and stays longer than Admin2 does, if the users put ② (Secretary's Office/Administration) near the end part of Section II, we consider that it refers to Admin3 instead of Admin2 and is correct even if it is on Admin2's side (Figure 8c). Specifically, although a participant could not understand the virtual landmark at the moment drawing it, he or she recalled the location correctly, we considered it to be correct (Figure 8b).

Table 3 shows how many landmarks were labeled correctly in each section of the route. Participants' memory of the route decreased significantly on Section II. As the participants put it, they could not remember the task or the route after a while. Stair3 and Elevator2 are most often correctly labeled, as they are functional landmarks and are at the end point. Participants also labeled Admin1 quite often. In Section II, the visually salient pillars only appeared 5 times while the administration office appeared 12 times.

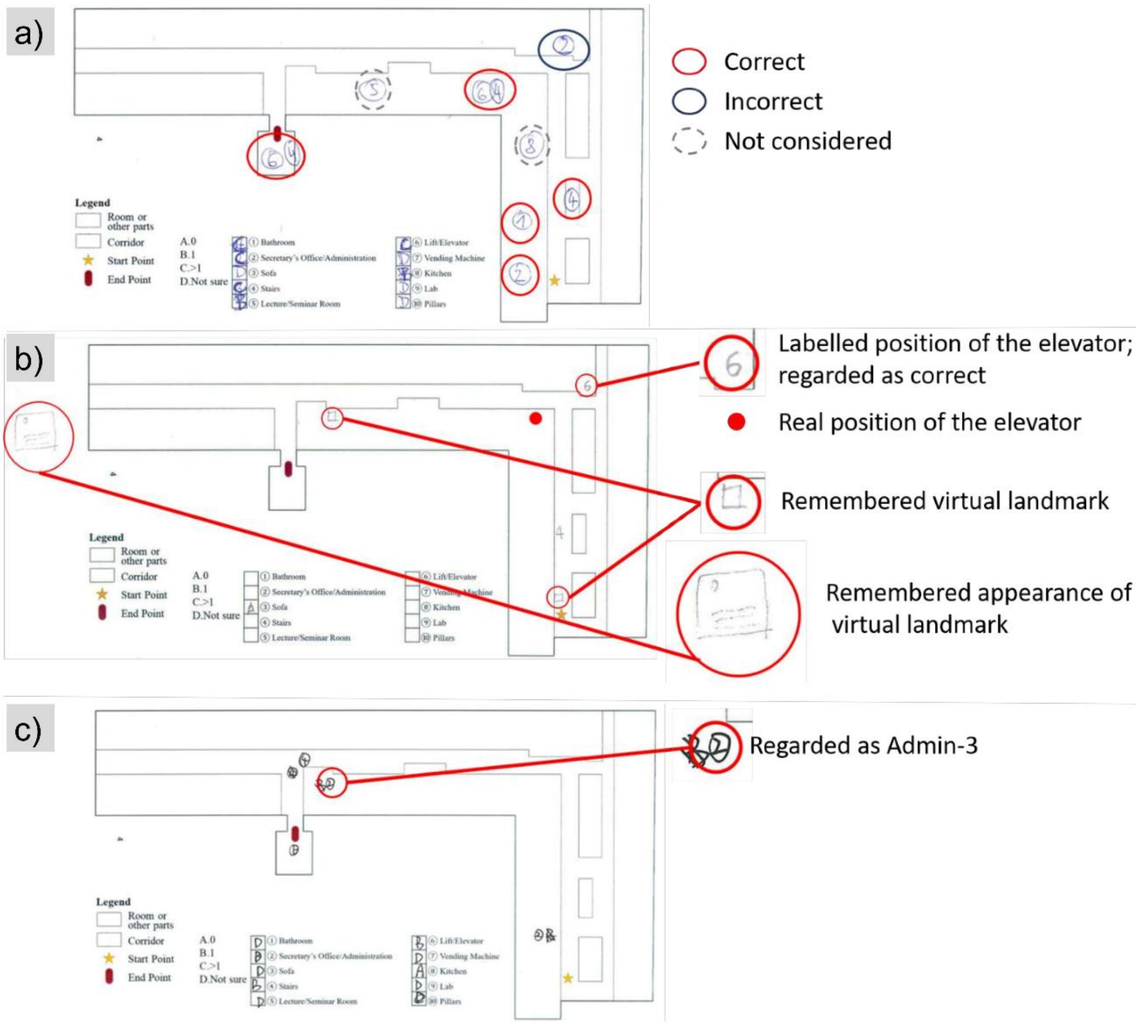

Figure 8 Examples of landmarks correctness analysis. 8a) A landmark is considered to be correct, incorrect or not considered. 8b) Example of special cases that are considered to be correct. 8c) ② (Secretary's Office/Administration) near the end part of Section II are considered as Admin3.

Route Section	Landmark	Count
Section I	Admin1	15
	Stair1	12
	Bathroom1	11
Section II	Stair2	11
	Elevator1	13
	Pillar1	3
	Pillar2	2
	Admin2	5
	Admin3	7
Section III	Bathroom2	2
	Stair3	15
	Elevator2	17

Table 3 Correctness of landmark locating.

Interview

The participants were asked about their general opinions on or comments on their walking experience (e.g., whether they think it is similar to daily walking), the comments about device and interface, and the advice on assisting spatial knowledge acquisition. Table 4 shows the summarized results of the interview from 27 participants (the record of one female participant was lost due to technical issues). Note that not every participant was asked every single question as the interview went differently according to each individual participant's answers.

General comments

For the general comments, 17 participants held positive attitudes towards the walking experience (Table 4, "General"), and some of them mentioned it as enjoyable, fun, playable or game-like. One participant said it was neutral. Others did not give any positive or negative comments.

14 participants said it was different from their daily walking experience. Specifically, when wearing HoloLens, 2 participants walked faster than usual while 5 others walked more slowly. 4 participants said walking wearing HoloLens was similar or almost similar to their daily experience. In both conditions, they did not pay much attention to the surroundings.

	Index	**description (number of participants)**	
General	**General Comment**	Neutral (1)	Positive (17)
	Walking with HoloLens is similar to daily walking experience:	Yes (4)	No (14)
	If not, when walking with HoloLens, you tend to walk:	Faster (2)	More slowly (5)
	Other	Like game (3)	
Device	**Device weight**	Not heavy (1)	Heavy (13)
	Other	Seeing "rainbow" (7)	
Interface	**General Comment**	Clear (10)	
	Arrow color	Good (1)	Not good (2)
	Other	Helpful (5)	Focused on arrows (11)
	Virtual landmark	Seen (22)	Not seen (3)
	Confidence of interpreting virtual landmark	Sure (12)	Not sure (11)
	Correctness of interpreting virtual landmark	Correct (11)	Incorrect (12)

Table 4 Summary of interview results

Comments on device

Comments on the device are shown in Table 4. 13 participants mentioned that the device was heavy, while 1 said it was not. 7 participants reported seeing “rainbows” on the lens, which was the reflection of hanging lamps. 6 participants said it was comfortable, while 5 others reported discomfort. A few (3) said it was acceptable or perfect for research but not for daily use, maybe because it does not fit into the life we are familiar with. 2 participants mentioned it was darker seeing through HoloLens. 2 participants said they had to bend head to see the arrows. Other comments include feeling dizzy or unstable display.

Comments on interface

Comments on interface design are grouped as “Interface” in Table 3. In general, arrows work well for guiding the way. 10 participants found the interface clear. 5 participants explicitly said it is helpful for navigation. One participant said the arrows are with proper color, while 2 others did not prefer the color. Many participants did not pay much attention to the real world, because they were focused on the salient arrows (11) or on the new things (1) or they trusted and relied on the software (2).

22 participants reported that they had seen the virtual landmarks. 12 of them were sure about the meaning (though not everyone interpreted it in the way we intended) while 11 were not and gave more than one explanation. The total number is 23 as in the interview we pointed out the virtual landmark to one participant who had not noticed it. Participants thought it referred to nearby objects (12), clickable menu (4), backend files of the software (3) or had difficulty understanding them (2). 11 participants interpreted the virtual landmarks correctly as “admin office”, “office” or “room”. 2 participants, who reported getting lost easily, regarded virtual landmarks helpful for learning the area. Another one located the start point with the help of the virtual landmark nearby and reported “here is the start point, because I remember the administration icon was there”. 3 participants said the virtual landmarks are not ideally designed because it is too flat (2) or the border is not perfectly cut (1).

Advice on interface design

We collected participants’ advice on interface design, especially for assisting spatial knowledge acquisition. Most advice is about hologram design, e.g., using lighter or smaller arrows and landmarks, and designing arrows of different colors to indicate up/downstairs. Animation and interaction of virtual landmarks and instructions are preferred, for example, they can jump, flash or show up according to user’s facing direction. Participants also suggested displaying fewer arrows or landmarks along the route but more around turns.

Other elements were also proposed, for example, overview maps. One participant proposed building a more immersive, VR-like environment by labeling the lines of walls/ceiling/floor to facilitate a holistic perception and allowing users to spare more attention out of the arrows. Another participant preferred a push window and a smartphone-like interface, so users could predict where the new info will be.

Other aspects

As an open question in the interview, participants were encouraged to comment on anything about their walking experience. This reveals unexpected findings. One interesting finding is that wearing HoloLens can influence more than just visual sense. For instance, one participant was sure that at the beginning of Section II there were stairs, while there was actually only a very slight slope and nobody else even noticed it. Another participant mentioned at the end of the interview that he/she felt the time flew differently wearing HoloLens. A third participant, who confirmed that he/she is not color-blind but has quite different eyesight for left and right eyes, regarded the yellow arrows as green.

One raised issue is safety, which has been foreseen. One participant said he/she almost hit on a closed glass door, as the arrow went through it. Such improper occlusion is predictable as HoloLens has difficulty detecting transparent objects and occluding holograms accordingly.

Video

The FOV of the videos taken by HoloLens is smaller than that of the participants. The device only shoots what can be seen through the screen while the participants could see through the transparent glass as well. Since 2 recordings were interrupted unexpectedly, the result is based on 26 records.

We analyzed participants' responses to the virtual landmarks based on the video clips. Admin1 showed up on 23 records, and 15 participants either said they saw it or turned head to look at it. Admin2, or at least part of it, showed up during 18 participants' walking, however, only one participant looked at it. Admin3 showed up for all the 26 records and 13 participants showed clear signs paying specific attention to the landmark, by either talking about it or turning head towards it.

As Admin1 was at the start point, it is possible that the participants had already seen it before the record started. Admin2 was far away from the arrows that most of the participants followed strictly, so it was very often at the quite left peripheral area of the whole FOV. Admin3 was next to the arrow, so more participants saw it than Admin2. However, participants also found it confusing as it is not close to the door.

The videos show a slight misalignment between the holograms and the real world during one participant's walking, and the holograms appeared "in" the walls. However, it was not severe, the participant did not mention this issue during the walking or in the interview.

Discussion

In this study, 28 participants, who were not very familiar with the study area, and had little experience with MR or VR technology, used HMD MR-based navigation aid to reach an unknown destination in an indoor environment. After walking to the destination and performing the tasks, all participants went back to the start point independently.

Our study shows that HMD MR is helpful and welcomed by the users for indoor navigation. All the participants reached the destination wearing HoloLens and went back to the start point successfully without the aid. The questionnaire reveals that the average participants have positive walking experiences. The HMD MR altered some participants' walking behavior, as they walked faster or slower than usual. Most participants simply focused on the arrows when walking wearing HoloLens. They did so because the arrows were salient or they trusted the arrows, or they were spontaneously attracted by the new experience. Either way, the first-time users tended to pay little attention to the physical surroundings. The physical discomfort was slight, and only 1 participant mentioned sickness. Unlike the study by W. Wang et al. (2019), where only the old female and the schoolchild thought HoloLens was a bit heavy after a long time use, "heavy" was raised by 13 out of 27 participants (average age = 29.6) in our study. It might be that in their study, participants use HoloLens in a small area while in this study participants need to walk around. However, the extra weight was acceptable as 17 participants gave positive comments on the general walking experience.

The hypothesis is confirmed by the user study that virtual semantic landmarks can assist spatial knowledge acquisition, even incidentally. The landmark locating task was hard for the participants as most of them paid little attention to the surroundings. The top 3 labeled landmarks are stairs, administration offices and lifts, which confirms the statement of Ohm et al. (2014) that functional landmarks, such as stairs and lifts, are most important for indoor navigation. The administration offices exceeded the visually salient pillars, the more common concerned functional landmark, i.e. the bathroom, and more widely located lecture rooms or labs, and ranked the second most. More specifically, in Section II, the pillars only appeared 5 times while the administration office appeared 12 times. This indicates virtual landmarks can help acquire the corresponding information in general. Besides, two participants with poor self-report SOD found the interface to be helpful to remember the route. This aligns with Carbonell-Carrera and Saorin (2018)'s finding that users with poor SOD benefit more from landmark-included virtual reality training. Another participant in our study located the start point with recalling the first virtual landmark, Admin1. Burte and Montello (2017) call for methods to assist people with poor SOD to attend to spatial features, as it is not the spontaneous behavior of such individuals. Our study confirms that the virtual semantic landmarks are useful to assist spatial knowledge acquisition, especially for people with poor SOD.

Participants believe that more consciously designed holograms and other elements on the interface can better facilitate spatial knowledge acquisition. The virtual landmarks or arrows can be smaller, with a lighter color or with more animation and interaction. Overview maps, push windows or lines highlighting the indoor structure may also be helpful.

Animation may also compensate the fact we found in the videos, that peripheral vision is not active enough to guide visual attention in MR environment. Many participants overlooked the virtual landmark Admin2, which was in a very peripheral position of the view field when the participants focused on the arrows. If the virtual landmarks could jump or flash, as the participants suggested, it may attract more attention, since motion is with very high visual guidance (Hall et al. 2016).

Although participants only mentioned interaction between users and holograms, more extensive interactions may benefit spatial knowledge acquisition as well. When the navigation tools enable sensory and social interactions, routes are better memorized (McCullough and Collins 2019). More spatial knowledge might be acquired from or interactions among different MR-based indoor navigation devices/users. Besides, designers can integrate some additional aids that may encourage users to interact with passers-by or give positive feedback to users' wayfinding behavior, and thus ease their spatial anxiety, encourage them to explore and improve their wayfinding skills (He and Hegarty 2020).

Unexpectedly, the user study reveals that vision is not the only sense influenced by visual augmentation. One participant drew a non-existent stair at the beginning of Section II. During the interview with him/her, we found that he/she has acrophobia (scare of height), which might make him/her more sensitive to the height change. With the limited FOV and decreased attention to the physical world, he/she felt the indoor height change and regarded it naturally as stairs. As 2-5% of the general population has acrophobia ("Acrophobia - Wikipedia" 2020), this needs to be looked into in detail to see if the misunderstanding influences the usage of MR in other fields or situations. For the participant who sensed time flew differently, he/she was also confused and did not explain any reason. As he/she did not mention whether the walking experience was different from or similar with the daily walking, we could not tell if it was because of different walking paces. Besides, we also found that somehow, users without color-blindness but with highly different eyesight in both eyes may see colors unexpected by the designer. These unexpected results are based on individual cases, but it is not clear whether they are common issues within a certain user group. We suggest that researchers consider these factors in future work, e.g., by including carefully designed questionnaires.

After all, MR is still a new technology to the general public and many cognitive issues remain to be solved. Although confirmed to be helpful in acquiring semantic landmark knowledge, virtual semantic landmarks are not natural objects. Their usage can be a two-edged sword, similar to other virtual elements. For example, Keil et al. (2020) found holographic grid improves distance estimation but worsens location memory performance. In this user study, it is not clear yet if this design compromises acquisition or awareness of other landmarks. Further standardized usability studies with control groups, quantitative measurements and statistical evidence are required to thoroughly understand the effects of such virtual elements.

Besides, this study was conducted almost in a passers-by-free environment, assuring a simplified study scenario. It remains an open question how the interface works with a more complex situation. For example, while many participants in this study suggested interactions and one participant asked specifically for more labels, the users went through almost empty corridors. We do not know yet how the users will handle a much busier environment.

Spatial knowledge acquisition and route retention are important for the repeating navigation tasks. Instead of active decision making, we propose to augment the reality with semantically salient landmarks and found that such landmarks could assist incidental spatial knowledge acquisition without much workload. Our study also suggests that with mixed reality, landmarks can be extended to more than visually salient ones.

Conclusion and Outlook

The study explored the influence of virtual semantic landmarks on spatial knowledge acquisition in HMD MR-based indoor navigation. Sketch map, landmark locating and interview results were used to analyze the influence. The results show that the HMD MR-based device is helpful for indoor navigation and is well accepted by users. The main complaint about the device was about its weight rather than cybersickness. Virtual semantic landmarks are helpful in incidental spatial knowledge acquisition and users believe they can benefit more from better designed holograms (color, position, animation). The influence of virtual semantic landmarks needs to be thoroughly explored with further standardized usability studies. The results of individual cases in our experiment also imply that HMD not only augments vision but also affects other senses, such as the sense of time and height, which is worth further research to make full use of the technology. Our user study was conducted in an almost passers-by-free environment. Nevertheless, it is among the first elaborate experiments of its kind and serves as a part of long-standing research effort to investigate how users learn to understand and confidently navigate in larger and complex indoor environments.

Data Availability

The datasets generated and analyzed during the current study are not publicly available as they contain information that could compromise privacy and consent of research participants, but they are available from the corresponding author on reasonable request.

Disclosure statement

The authors declare no conflicts of interest.

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App.D Liu B, Wang S, Amrullah C, Ding L, Meng L (2022) Structural Information Learning and Interface Design with Mixed Reality.

Additional Contribution in Submission.

Structural Information Learning and Interface Design with Mixed Reality

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Abstract: Spatial knowledge acquisition is an especially significant topic for MR-based indoor navigation. Spatial knowledge can be acquired incidentally, and augmented semantic landmarks assist the incidental learning of corresponding knowledge. With the benefits of convenience, users instinctively tend to ignore the environment with navigation aid, which leads to inattentional blindness. This phenomenon is even more severe in MR-based navigation because rich visualization draws too much visual attention. In this study, we explore how the navigation interface influences spatial knowledge acquisition and the individual preferences of the navigation interface. Specifically, we conducted a user study involving 40 users and tested if users' spatial memory resembles the visualization and whether point-like augmented structural landmarks can help users perceive the structure of the indoor environment. We used point-like landmarks to show the corridor along the route during navigation. The results show that most users can remember the augmented corridor incidentally. Seven out of 40 users cannot remember the corridor. For safety reasons, we recommend using structural landmarks instead of pictorial landmarks for structural information. Besides, we design a browser-based tool - Design-It-Yourself tool (DIY) - to collect ordinary users' preferences for indoor navigation interfaces. The results show that users' preferences for interface design diversify. Adaptive/adaptable MR-based indoor navigation interfaces are needed. This study supports a better user experience and better learning of structural information in MR-based navigation and safety-related application.

Keywords: indoor navigation, mixed-reality, spatial knowledge acquisition, structural landmark, adaptive/adaptable interface design

Introduction

Spatial learning is necessary for animals' survival (Dehaene 2021). People learn about the environment during their navigation and develop the mental map of it. The acquired spatial knowledge is used for our daily activities (McCullough and Collins 2019; Burte and Montello 2017), professional operations (Li et al. 2018), and fast decision-making in emergence (Lin, Cao, and Li 2020). Indoor spatial learning is especially essential since modern people spend most time indoors (Liu et al. 2022). The global indoor PLAN market (positioning, localization and navigation) is booming and expected to reach $ 28.2 billion by 2024, at a Compound Annual Growth Rate (CAGR) of 38.2% since 2016 (Goldstein Research 2019).

Fewer indoor location-based services (LBSs) are ready to use compared to their outdoor counterparts. A reason hindering the development of indoor LBSs is the difficulty of indoor positioning. More techniques are becoming available now, such as Bluetooth beacons, visual markers, and visual recognition (Liu et al. 2022). These emerging techniques popularize indoor LBS; hopefully, indoor LBS will also improve people's learning of indoor spaces. Indoor spatial learning is difficult. People get lost more easily doors, mainly influenced by three factors: the spatial structure of the building, the cognitive maps that users construct as they navigate and the strategies and spatial abilities of the building users (Carlson et al. 2010).

Mixed reality (MR) is among the diversified indoor positioning techniques. It augments the physical world with virtual elements. MR is valued for its entertainment to the public, self-containing and low requirement for device maintenance for the development. These characteristics make it suitable for indoor LBS.

MR's influence on learning is unclear. Evidence has shown that MR improves learning attitudes in school and university education (Tang et al. 2020). It is also used for the training of employees (Harborth and Kümpers 2021). However, current head-mounted MR devices (HMD MR) are also blamed for the limited FOV (Field of View) and the risk of leading to the cognitive tunneling and inattentional blindness. In spatial learning, HMD MR is found to improve spatial learning through active involvement in decision-making (Wen et al. 2014), and incidental learning of landmarks (Liu, Ding, and Meng 2021). However, learning indoor structures for people's mobility and fast decision-making is more complex and has not been tested yet.

Adaptive and adaptable designs are also proposed in navigation (Truong-Allié et al. 2021) and other LBS services (Bartling et al. 2022) to improve user experience and spatial learning. People benefit from personalized learning (Cock et al. 2021). Understanding ordinary users' behavior and preferences are necessary for such designs (Liao et al. 2019; Huang, Mathis, and Weibel 2022; Bartling et al. 2021; Liu, Ding, and Meng 2021). However, collecting users' feedback about HMD MR is not easy. Not many ordinary users possess HMD MR, and they must be on-site with MR experts to test the MR experience. Moreover, the collection of feedback is time- and effort-consuming. Easily accessible tools are needed to involve more users in the MR interface design pipeline and to accelerate the adaptive/adaptable design.

This study focuses on the learning of indoor structures during HMD MR-based navigation. We specifically examined the influence of MR visualization on spatial learning. We test whether the spatial memory resembles the visualization, and whether structural information represented by point landmarks can be perceived correctly and integrated structurally. We also developed a browser-based tool to involve ordinary users in interface design for MR-based navigation, collected users' feedback, and summarized the findings of their preferences.

Spatial learning and indoor structure

Spatial learning is essential for our daily life, especially indoors.

Spatial knowledge is essential in our daily life (McCullough and Collins 2019; Burte and Montello 2017), some expert operations (Li et al. 2018), and decision-making in emergencies (Lin, Cao, and Li 2020). Tools like navigation apps and facility managing apps seem to lessen the significance of spatial learning. However, long-term reliance on such assistance also causes some risks(Xu et al. 2022).

Spatial knowledge is categorized as landmark, route, and survey knowledge (Ishikawa and Montello 2006). Landmarks are visually, semantically, or structurally salient objects (Raubal and Winter 2002). They serve as intuitive references in people's navigation and are helpful in navigation and spatial learning (Ligonnière et al. 2021; Fang et al. 2020; Liu, Ding, and Meng 2021). MR has been proven to assist the learning of indoor semantic landmarks.

Learning about indoor space is especially important. Modern people spend most of their time indoors (Klepeis et al. 2001), and indoor spatial knowledge is necessary for their mobility and some professional tasks, such as facility management, damage evaluation (Kamat and El-Tawil 2007), and rescue (Snopková et al. 2022). Still, learning the indoor space and navigating indoors is difficult (Bauer, Müller, and Ludwig 2016). The spatial structure of the building is one of the three factors that influence indoor navigation (the other two are the cognitive maps constructed during people's navigation and the individual strategies and spatial ability) (Carlson et al. 2010).

Structure information is essential in various scenarios.

MR is widely used for assisting indoor tasks aside from navigation. Indoor structure information is essential in many such scenarios. For example, MR is used for safety inspection and instruction (Li et al. 2018). It ranges from building assessment and disaster-related structural damage evaluation conditions (Kamat and El-Tawil 2007) to evacuation in emergency and its training (Catal et al. 2020). MR also benefits the professional training of the constructors (Bosché, Abdel-Wahab, and Carozza 2016). In such scenarios, the operators need to make decisions fast (Kamat and El-Tawil 2007). Entirely relying on the assistant systems is insufficient in such cases. The human operator needs to be involved in decision-making.

Identifying indoor structures is difficult for people.

Different from visual or semantic landmarks, structural landmarks are not one single point. Its saliency is an areal characteristic. Identifying a structural landmark requires perceiving a specific area and is especially difficult indoors. The indoor environment always has limited visibility, and different buildings can be pretty distinct with solid styles. For example, the university/hospital buildings might be remarkably symmetric, while a museum is more stylish. Therefore, it is difficult to expect, identify and remember the indoor structure.

Structural landmarks, such as open spaces and stairs, can contribute to a more cognitively-sounding route planning algorithm (Vanhaeren et al. 2020). Structural landmarks, e.g., elevators, corridors, exits, and doors, are important for an emergency. However, learning structural information with MR can be difficult. Structural landmarks are ignored in the work of Liu, Ding, and Meng (2021); only 13 and 11 out of 28 participants in their study remembered the elevator and stair, respectively (Figure 1, generated from their work). It shows that the elevator and stairs are ignored, although they are functional and should attract the most attention (Liu, Ding, and Meng 2021). This can be critical in an emergency.

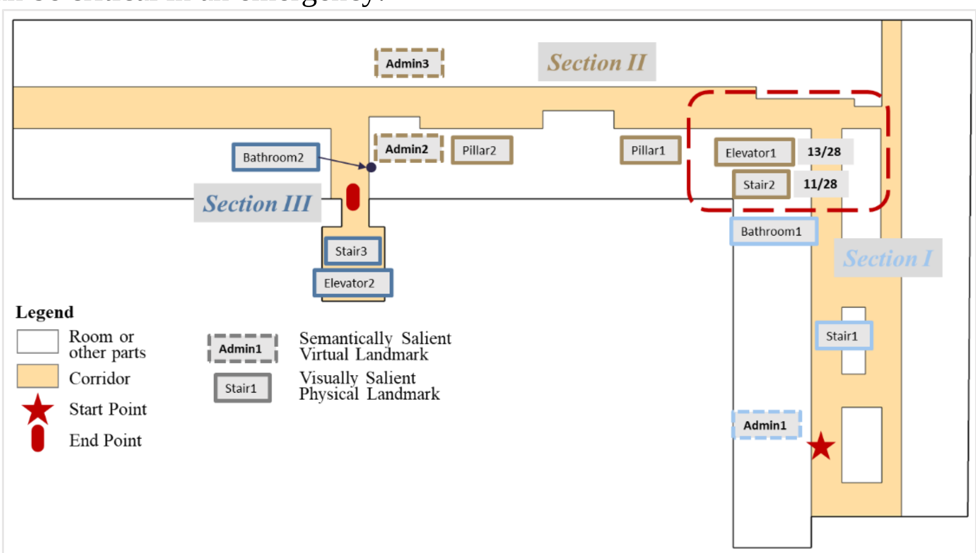

Figure 1 Landmarks in the virtual semantic landmark user study.

The study of improving structure learning.

Indoor structural information is usually displayed in the evacuation or floor plan and shown as icons (Figure 2). Some signs also show the structural information, e.g., emergency exits. But familiar visitors seldom learn the structural information intentionally. Besides, with time pressure, users might have no time to refer to such information or simply overlook it. Structural information is vital for first-person-view games and is usually visualized as small maps. Such overview maps are also introduced to MR-based navigation (Thi Minh Tran and Parker 2020). However, they occupy more space and decrease the real world’s visibility. This may increase incidental blindness and thus be risky.

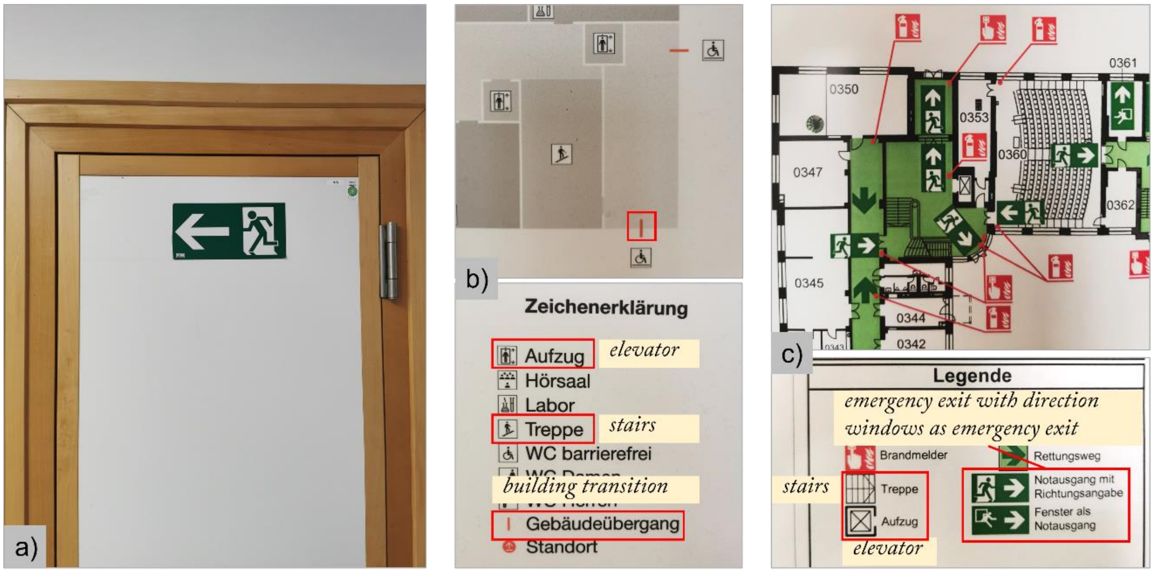

Figure 2 Pointlike visualization of structural information. A) on the door, b) on the floor plan, and c) on the evacuation map.

Using signs to visualize structural information would be constant with the visualization of other landmarks and save place for other visualizations. However, it's unclear whether users can perceive the indicated information structurally. We can usually recall structural information with memory and reasoning. For example, we would assume there are stairs nearby if we know the location of an elevator. But there is no guarantee that we could quickly recall the stairs spontaneously, especially in emergencies. It is essential to perceive such information "structurally" and integrate it into the mental map. Pointlike landmarks (similar to the signs in Figure 2) visualize the structure information in MR-based first-person-view navigation. It's unclear if the users' memory of the structure information resembles the visualization, and if the memory of structural information is memorized as points.

Visualization and adaptive/adaptable interface design for navigation

Despite the importance of indoor structural information and spatial learning, few users with assistance devices learn it intentionally. Incidental spatial learning has been proven to be possible (Liu, Ding, and Meng 2021; Wenczel, Hepperle, and Stülpnagel 2017; Rehman and Cao 2017; Gramann, Hoepner, and Karrer-Gauss 2017), especially for those people with good sense of direction (SOD) (Burte and Montello 2017). The difference between people with good and poor SOD is mainly on incidental spatial learning, not intentional learning. Improving incidental learning by proper visualization is feasible and benefits people with poor SOD.

Learning results are not only influenced by the learning intention but also by the learning process (Kelly 2012). It's difficult to flexibly apply the obtained knowledge in other situations (Roskos et al., 1998), and spatial memory is tied to the tool (Xu et al. 2022). These findings are based on map-based navigation. It's unclear if it holds in MR-based navigation, as it is a first-person view. For example, if people's spatial memory resembles how they learn it.

MR interface design also influences spatial learning and needs to be personalized. Recently, user-centric and contextual map designs have been investigated (Opach and Rød 2021). Adaptive automation aids are also proven to better balance the usability and learning in navigation (Rehman and Cao 2017). Requirements for map display vary according to different spatial tasks (Thi Minh Tran and Parker 2020) and task phases (Curtsson 2021; Cock et al. 2019). Different users found different buildings difficult to navigate (Carlson et al. 2010), which means different information is needed. Besides, in Makimura et al. (2019)'s study about the visual effects of a turning point for MR-based outdoor navigation, the route likeability varies among the users. People's needs for the interface tend to be different. For example, people with poor SOD benefit more from augmented semantic landmarks (Liu, Ding, and Meng 2021) and landmark-based navigation (Li et al. 2014). Therefore, adaptation is necessary for MR-based navigation to meet users' expectation and their physical and perceptual abilities (Curtsson 2021).

User Study – Visualization's influence on spatial learning

User study setup

The user study was conducted on the city campus of the Technical University of Munich (TUM). The study area is shown in Figure 3. There are three corridors in the study area (Corridor1-3, Figure 3). The two on the right side are labeled by virtual iconic pointlike landmarks; the one on the left side is not labeled with landmarks. The path is also visualized in two ways: with lines (WL) and no lines (NL, Figure 4) to test if users learning of the path resembles its visualization. Microsoft HoloLens 2 was used in the user study. Forty participants took part in the user study and were randomly set to one of the two groups (N_{WL}=N_{NL}=20). The details of the user study are described in Liu et al. (2022) but with different research objectives.

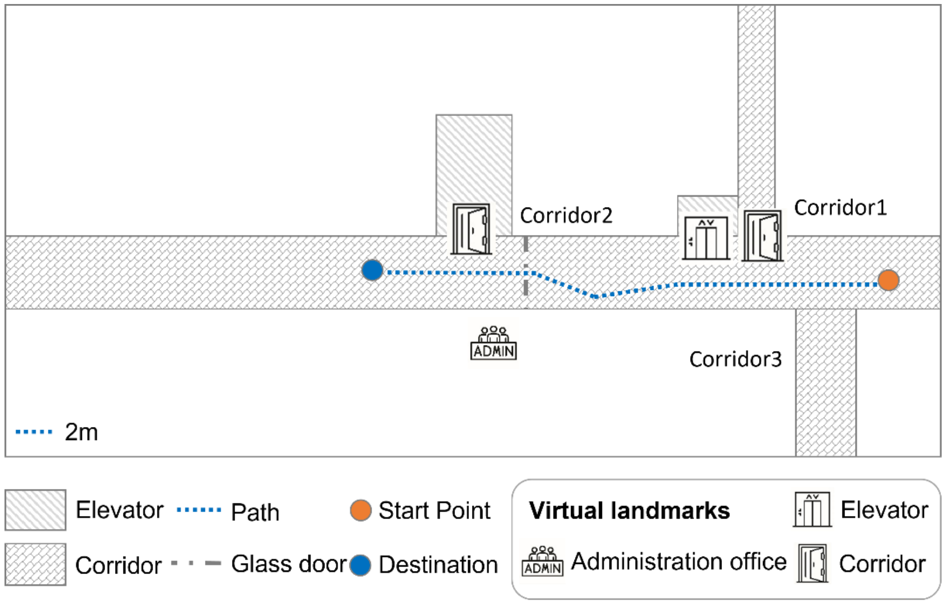

Figure 3 Study area

Figure 4 Visualization of WL group (left) and NL group (right).

Procedures

The user study consists of a pre-questionnaire, a walking session, a post-walking questionnaire, and a semi-structured interview. The general procedure is described below (see details in Liu et al. 2022).

To assess the results of spatial learning, we first ask the participants to draw a map of the study area on a blank sheet of paper (with the task description) without a time limit. The participants were encouraged to outline every detail they could remember. Once finished, the participants were asked how confident they were about the sketch maps. Then, the participants needed to choose the study area structure (Figure 5). A and D are without corridors, B and E are only with the augmented corridor (Corridor1), and C and F are with the augmented and unaugmented corridors (Corridors 1 and 3). Options D-F include a turn as there was an artificial turn during the navigation (Liu et al. 2022). Finally, the participants' opinions on the current interface and suggestions for future design were collected in a semi-structured interview. The interview results show that the preferences are personal and diverse.

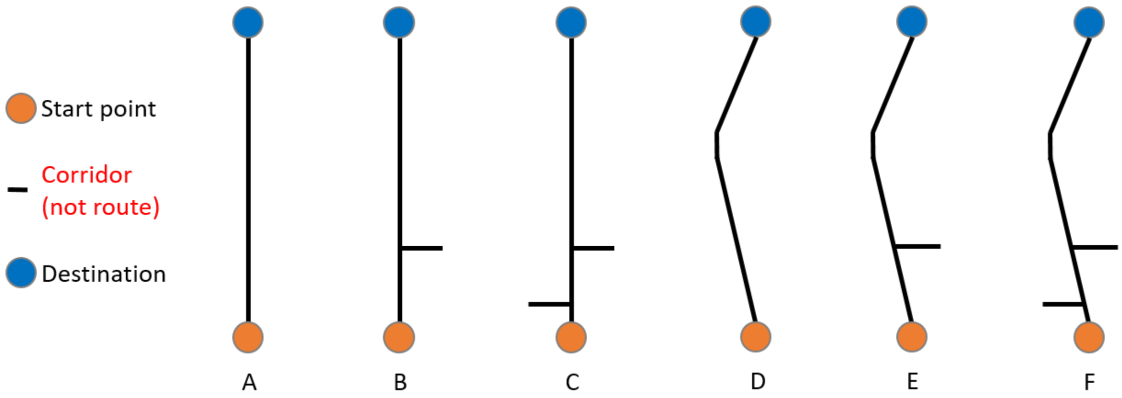

Figure 5 Options for the study area structure

Results

We investigated the path and corridor visualization that participants adopted in the sketch maps, reflecting participants' memory of the study area. The location of a corridor is regarded as correct if it's on the correct side. The corridor is regarded as represented structurally if it is labeled with *corridor*, *hall*, *staircase*, *exit*, or drawn as a line; it is regarded as non-structural if it is marked with *door* or drawn as a rectangle without further explanation.

Table 1 Sketched corridors (Cd: corridor).

Group	Cd location	Cd1	Cd2	Cd3	Cd Structure	Structure info	False Cd	
							right side	left side
WL	28	16	10	2	22	14	1	1
NL	29	16	12	1	20	11	1	1
Sum	57	32	22	40	42	25	4	

Table 1 summarizes the number and visualizations of corridors (Corridor1, 2, and 3) in sketch mapping. We first counted the correctly located corridors. If all participants located the three corridors, i.e., the maximum value is 120 (sum). The WL participants correctly located 28 corridors; for the NL participants, the value is 29. Together, all the participants located the corridors correctly 57 times. The corridors are visualized structurally 22 times in the WL group and 20 times in the NL group. Fourteen participants in the WL group and 11 in the NL group drew corridors in structural ways.

Specifically, in the WL group, Corridor1, 2, and 3 are correctly located for 16, 10, and 2 times, respectively. In the NL group, the values are 16, 12, and 1. The augmented Corridor1 and Corridor2 are labeled much more than the non-augmented Corridor3. Besides, four false corridors are drawn. That is to say, some participants recalled non-existent corridors.

Table 2 Results of structure choosing task

group	no Cd	with augmented Cd	with augmented and non-augmented Cd	Others

	A	D	B	E	C	F	B/C
WL	3	0	13	0	4	0	0
NL	4	0	10	2	3	0	1
sum	7		25		7		1

For the structure-choosing task (Table 2), seven participants chose A, which means they remembered the study area as with any corridors. Most participants chose the options with only the augmented corridor, i.e., B or E. Seven participants chose the options with both the augmented and non-augmented corridor. One NL group participant was unsure about the non-augmented corridor and could not decide between B or C.

Table 3 Visualization styles of the path.

group	arrow	line	line+arrow	line+dot	dotted line	sum
WL	3	7	8	1	1	20
NL	12	6	2	0	0	20
sum	15	13	10	1	1	40

There is a significant difference in the path visualization between the two groups of WL and NL (Table 3). Arrows are used most in path visualization. Three participants in the WL group and 12 in the NL group used arrows to indicate a path. Seventeen participants in the WL group used the line to visualize the path, among which 7 used only line, 8 used line with an arrow, 1 used line with dot and 1 used dotted line. Only 8 participants in the NL group used line, 6 of them used line and 2 used line with arrow.

To summarize, in the task of sketch mapping, twenty-five of the 40 participants illustrated the corridor in a structural way. In the task of structure selection, the correct number is higher with 33 participants remembering at least one corridor. This indicates that with reminders like the options in structure choosing task, users tend to remember the structural information. But the structural information is not instinctively learned and integrated as the sketched maps show.

For the path visualization, the participants in the NL group are more likely to use arrows, while most participants in WL group used lines to indicate the path. In general, they tended to use the visualization styles they saw in the interface to represent the path. The participants' visualization of the study area resembles the interface.

A browser-based DIY MR navigation interface design tool

Ordinary users' preferences for the navigation interface are essential for adaptive and adaptable design. It clarifies which information to be included and which visualizations should be provided. Ordinary users' expectation of the MR-based navigation interface is not fully understood. Involving ordinary users in interface design for HMD MR is difficult as the device is not accessible to them yet. Besides, the user study shows the diverse users' preferences for interface design, and an adaptive/adaptable MR-based indoor navigation interface is needed. Therefore, we built a web-based DIY (Design-It-Yourself) tool that allows the users to design their own interfaces and collected 12 users' preferences using this tool.

Development

The DIY tool is developed using JavaScript. Frameworks used include NodeJS, ReactJS, Redux, and FabricJS. NodeJS is open-sourced, enhances performance, server development, unit testing, and scalability, and is used as the back-end framework. ReactJS is an open-source front-end library to develop user interfaces for websites and web apps in a structured way and is used for user interface design.

Redux is a predictable state container for JavaScript apps and improves application performance consistency among different environments (client, server, and native).

FabricJS is a framework for working with HTML5 canvas elements and is used for interactive functions. The first version supports the accessible design of point icons.

With the DIY tool (Figure 6, left), the users can change images of the scenes and add and adjust icons (floorplans, navigation icons, room icons, and hallways, Figure 6, right) and texts. Static images serve as the "real world" in MR-based navigation. Floor plans are the overview map of the area. Navigation icons show the accessibility of the space. Room icons represent the semantics of the room. Hallways icons show the structural (e.g., doors), functional (e.g., info desk), and other objects in the hallway. Users can also add texts. The location, color, and size of these icons can be changed.

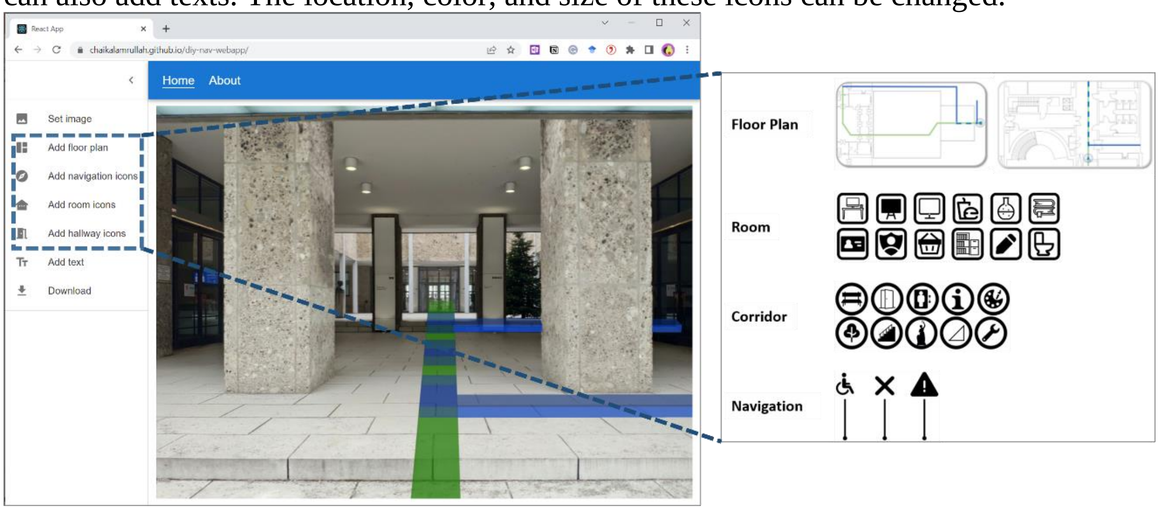

Figure 6 DIY interface and the icons directory

Example images along a real route in the TUM campus are provided. A first-person video taken by HoloLens 2 navigating the campus is provided to the users as an experience closer to a real MR navigating experience.

Individual preferences for MR-based indoor navigation interface

The usability of the DIY Navi-WebApp is tested. Twelve users used the DIY tool to design navigation interfaces on 3 or 4 images[1]. The interfaces are analyzed, and their comments on the DIY app are collected.

[1] DIY-Nav-WebApp, https://chaikalamrullah.github.io/diy-nav-webapp/.

The images are sequenced as a prepared travel from the starting point to the endpoint (Figure 7 a)). The photo was taken by mobile phone on December 23rd, 2021, with 4032 x 3024-pixel resolution (Figure 7 b) and c)).

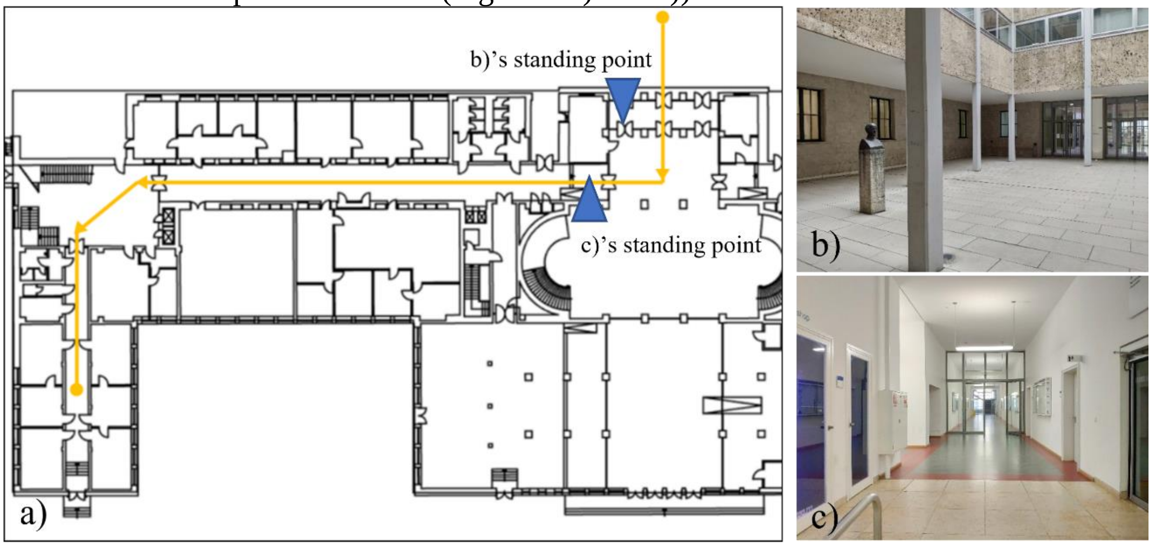

Figure 7 Setting in DIY tool. a) the prepared route on TUM main campus. b), c) examples of sequential images.

We analyzed all users' designs and found that the preferred icon colors varied among users (Figure 8a)). There are some color preferences for different icons. For the stair icon, users tend to like the yellow-red gradient; for the info-board icon, they like white and black; for the plant icon, green gradation is preferred; for the navigation icon, green, yellow and white are among the most preferred ones, while for door icon, they are green, blue and white.

The summary is mainly on the icon size and location. The results show that the desired settings vary for different landmarks (Table 4). The floor plan icon is generally placed in the corner or edge of the image with a size of 400*300 pixels. Users prefer a dynamic orientation that follows the user orientation in a fixed north direction. The navigation icon is placed on or near the intersection of the paths, at the height of 1.5 – 1.7 m, and the average size is 0.3 m*0.3 m. The room icon is placed in the middle or on the edge of the door, at the height of 1.5 m, and the average size is 0.5 m*0.5 m. Besides, the results show that if more than one icon is in the same area, most users visualize the room icon instead of the corridor or navigation icon. The position of the corridor icon depends on the landmarks, e.g., the info-board icon is placed above the object to avoid covering the information content. Still, the door icon is placed in the middle of the object. The average size for the corridor icon is 0.4 m*0.4 m. We generate a user interface based on current user preferences (Figure 8b)).

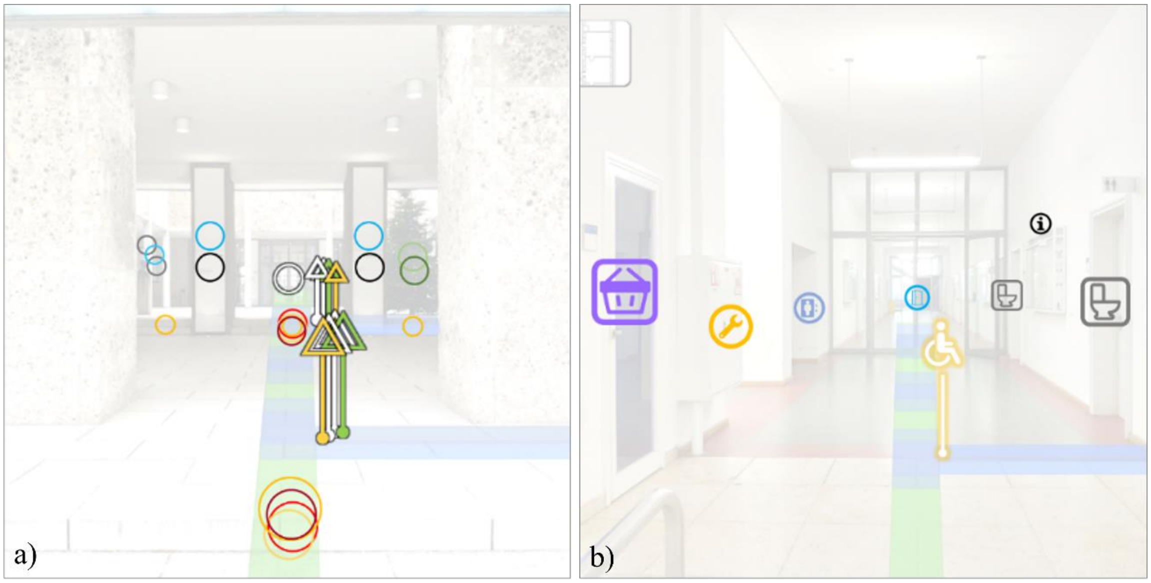

Figure 8 Users' feedback on DIY. a) Compilation of users' design (text is excluded). b) example of interface design based on users' design.

Table 4 Users' design of the icons on the navigation interface

	size/pt	size / m	position
Floor plan	400*300	-	corner/edge of the image; dynamic orientation
Navigation	-	0.3*0.3	on/near intersections; 1.5-1.7 m from the floor
Room	-	0.5*0.5	in the middle/on the edge of the door; 1.5 m from the floor
Corridor		0.4*0.4	in the middle/above the object

Discussion

Structure information is vital in indoor navigation, especially in emergencies. In this study, we conducted an HMD MR-based user study to test the learning of structural information during navigation.

The results of the user study show that the pointlike landmarks can be interpreted as structural information by most users, especially with extra hints, e.g., the options in our research. However, the results also show that the corridor is not naturally regarded as an essential object in users' mental map. This might hinder their evacuation in an emergency. The results of path visualization indicate that spatial memory resembles the visualization used in the interface. Therefore, using structural landmarks instead of pictures to show structural information might be helpful. For example, using horizontal lines to indicate corridors and using vertical lines to indicate elevators.

To further collect the ordinary users' design ideas and preferences, we developed the browser-based DIY tool for MR navigation interface design. We summarized 12 users' design results and generated an example interface based on the findings. The results show that ordinary users' preferences for the visualization vary according to the information type. Adaptive and adaptable interface design should be used in HMD MR-based navigation.

In the future, more design options and open functions will be added to the DIY tool. More ordinary users are to be invited. Besides, when MR is widely used, the interface will be different. It's not merely a *how-to-design* problem but also a *contextual* issue. Augmentation other than vision, e.g., audio instructions (Magnusson, Danielsson, and Rassmus-Grohn 2006) or smell landmarks, can be integrated into MR-based navigation. Under which situation the user using the navigation service should also be considered.

In general, the DIY tool, the theoretical interface design guidelines, and the practical MR-based navigation interface will iteratively evolve together.

Conclusion and future work

We explored the visualization of structural information's influence on learning of indoor structure during HMD MR-based navigation. We conducted a user study involving 40 users, and the results confirm that users' spatial memory resembles the visualization used in the interface in HMD MR navigation. The pointlike augmented structural landmarks can help users perceive the structure of the indoor environment incidentally. However, not all users can perceive them as structural information. Therefore, we recommend using structural landmarks instead of pictorial landmarks representing structural information for safety reasons.

To better understand users' personal preferences, we built a browser-based DIY tool and collected 12 users' interface designs. The DIY tool is intuitive to use. The results show that users' preferences for colors, landmark size and position vary according to landmark category. Besides, the users' preference for interface design diversifies. In the future, we will provide more design options and open functions with the DIY tool, involve more users and consider the contextual issues to design an adaptive/adaptable MR-based navigation interface.

This study supports a better user experience and learning of structural information during MR-based navigation and other related applications.

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Differences in the Gaze Behaviours of Pedestrians Navigating between Regular and Irregular Road Patterns

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Abstract: While a road pattern influences wayfinding and navigation, its influence on the gaze behaviours of navigating pedestrians is not well documented. In this study, we compared gaze behaviour differences between regular and irregular road patterns using eye-tracking technology. Twenty-one participants performed orientation (ORI) and shortest route selection (SRS) tasks with both road patterns. We used accuracy of answers and response time to estimate overall performance and time to first fixation duration, average fixation duration, fixation count and fixation duration to estimate gaze behaviour. The results showed that participants performed better with better accuracy of answers using irregular road patterns. For both tasks and both road patterns, the Label areas of interest (AOIs) (including shops and signs) received quicker or greater attention. The road patterns influenced gaze behaviour for both Road AOIs and Label AOIs but exhibited a greater influence on Road AOIs in both tasks. In summary, for orientation and route selection, users are more likely to rely on labels, and roads with irregular patterns are important. These findings may serve as the anchor point for determining how people's gaze behaviours differ depending on road pattern and indicate that labels and unique road patterns should be highlighted for better wayfinding and navigation.

Keywords: road pattern; orientation; shortest route selection; eye tracking

1. Introduction

Road patterns provide fundamental information for mobile activities, such as wayfinding, route planning and automatic navigation; however, they are also complicated. Road patterns vary in heterogeneity, connectivity, accessibility, interconnectivity [1], etc. [2,3]. These sophisticated systems not only impact the performance of transportation systems [4] and land use [5] but also strongly influence people's behaviours [6–10]. Many researchers have focused on the geometric attributes of road patterns and navigation solutions based on shortest time/distance routes [11,12] or other objective conditions [13]. However, people do not act solely based on geometric attributes. For example, drivers frequently do not take the shortest time route, and pedestrians have even more freedom in their movement choice [14]. When selecting a route, people tend to choose straight roads near the origin [15]. Pedestrians' perceptions of travel time are influenced by the network structure [2,16], which may influence their route selection. Therefore, it is necessary to investigate how people perceive and interact with road patterns and which information is important in this process.

Researchers have long been interested in the influence of road patterns on behaviour, such as driving performance, traffic safety [17] and route choice. Jacob et al. [18] and Green [19] found an increase in workload for drivers at smaller-radius and higher-deflection-angle curves in rural areas. Contrary to the common opinion that bends are dangerous for traffic, Haynes et al. [20] found that from a district perspective, straighter roads result in more crashes, and fatal road crashes are negatively related to the angle of roads. Zhang et al. [21] analysed the associations between non-motorist (i.e., pedestrians and cyclists)-involved crashes and the road network structure in Alameda County, California, and found that more intersections between pairs of roads tend to be safer for pedestrians. This study indicated that planners could block cut-through paths to improve traffic safety for pedestrians. However, the inconvenience caused by more intersections might prevent pedestrians from using them, which highlights the importance of considering people's feelings. In addition, people's route choices are also affected by road patterns, as shown by studies based on global positioning system (GPS) commute routes [2,16], actual walking conditions [22–25] and experimental conditions [26,27]. Research by Hochmair and Karlsson [28] on strategy preference in route selection indicates that different cognition processes occur between map-based and view-based navigations. For example, map-based route choice tends to include longer initial straight segments, while view-based users prefer short segments. Both Parthasarathi, Levinson, and Hochmair [2] and D'Acci [25] found that the road pattern influences pedestrians' time perception, with participants in the latter study preferring curvy roads.

Researchers have attempted to explain these behavioural differences. Behaviour-based studies in the physical world indicate that these differences may be related to the influence of road patterns on the judgement of geospatial metrics. Byrne [29] found that participants tend to overestimate the lengths of short routes and routes with major bends but not straight routes. Meanwhile, the estimations of intersection angles tend to be approximately 90° regardless of the actual angle (60–70° or 110–120°) in their residential neighbourhood. R. Montello [30] asked sixty pedestrians in three testing areas (one orthogonal and two oblique to the local grid pattern) to point to several nonvisible local targets or the main route direction. He compared the pointing accuracies and response times in these grids, and the results showed that the participants pointed more accurately with orthogonal streets than oblique streets. Due to complicated conditions in the real world, recent studies directly examine cognition processes with different road patterns in highly controlled laboratory conditions. For example, Liu et al. [31] reported research on cognition with different road patterns based on an fMRI (functional magnetic resonance imaging) experiment. They observed greater activation in cognition- and eye-movement-related brain areas in an orientation task with an irregular road pattern (compared with a regular road pattern), which indicates that orientating with an irregular road pattern is more difficult. These studies show that people's behaviours and cognition can be influenced by road patterns. However, as the road patterns in such studies are integrally regarded, it is difficult to clarify the aspects of the road pattern responsible for the differences. In this study, we separately analysed road and labels to distinguish the influencing component.

Eye-tracking technology, which is based on the eye-mind assumption [32], is commonly used to determine how people process information [32–36]. Because walking on roads requires considerable visual information and many attention switches, eye-tracking technology is applicable for navigation [37] and road-related [34,38] research. Hepperle and von Stülpnagel [39] compared gaze behaviour during intentional and incidental route learning and retrieval and found that the main difference pertained to the objects that the participants did not view. Liao et al. [40] used eye movement data to infer pedestrians' navigation tasks from five possible tasks and obtained a total classification accuracy of 67%. Fotios et al. [38] investigated the proper illumination design for pedestrians after dark by analysing where people fixated their attention and concluded the importance of providing sufficient illumination for other people and paths. However, this study was conducted during a walking period and did not specify certain tasks. Kitazawa and Fujiyama [41] analysed participants' eye tracking data while walking and found that pedestrians usually focus on the scene directly in front of them and that the information-processing space resembled a cone. Trefzger et al. [42] indicated that pedestrians and cyclists paid the most attention to the path during navigation. Giannopoulos, Kiefer, and Raubal [43] also applied eye-tracking technology to assist in the navigation of pedestrians and installed their

GazeNav app on a smartphone. This app makes the smartphone vibrate if the user looks at the correct street. These studies indicate that eye movement data are valuable in road-related research.

In this study, we aimed to identify pedestrian gaze differences between regular road patterns and irregular road patterns for navigational tasks and identify the roles of label and road information in this process. We categorized road patterns into irregular and regular patterns, asked participants to perform orientation (ORI) and shortest route selection (SRS) tasks using screenshots of the street view in both types of road patterns, and recorded the participants' eye movements during the tasks. By analysing eye movements over road and label information, we investigated the information that is important for navigational tasks and the differences among distinct road patterns. The results provide insights into improved road designs.

The second section of this paper introduces the experimental methods, including the experimental design overview, participants, apparatus, materials, procedure and data analysis methods. The third and fourth sections report the results and discuss the results, respectively. The fifth section concludes this study and proposes future work.

2. Materials and Methods

2.1. Experimental Design

In this study, roads were classified into two categories according to their patterns. Roads with orthogonal intersections and straight segments were regarded as regular road patterns, and those with non-orthogonal intersections or curved segments as irregular patterns [39,44]. We applied a within-participants design, where participants were instructed to perform ORI and SRS tasks in both patterns. These tasks were chosen because they presented a sense of orientation and distance. As part of a large-scope project of cognition research, this eye-tracking-based study shares a similar experimental design with previous work reported in [31]. However, the results of this previous study only confirmed the influence of road patterns and could not explain which part of the road pattern was attributed to in the influence.

The experiment was performed on two consecutive days. On Day 1, participants were instructed to become familiar with two areas—an area with a regular road pattern and an area with an irregular road pattern via street view maps. On Day 2, the participants accomplished a set of ORI and SRS tasks based on the previously learned areas, while their eye movements were recorded. Although this study was based on a newly learned road network and participants were perhaps not able to create a complete cognitive map, this map was not necessary to perform a successful geospatial task [45]. Before the experiment, we conducted a pre-test in which five university students from Beijing Normal University (BNU) participated to verify the materials and procedure in the experiment.

2.2. Participants

Twenty-three students who were recruited via online ads from universities in Beijing participated in the experiment. Two of the students did not complete the experiment due to reported difficulties in learning or unease during the experiment. The remaining 21 participants (mean age = 22.4, SD = 2.3; 7 males and 17 females; 7 with geography-related background) completed the experiment. With respect to the preferred reference system, six participants reported a preference for an allocentric reference system (i.e., using east/west/north/south) for wayfinding, ten preferred egocentric (right/left) and five reported no preferences and used both.

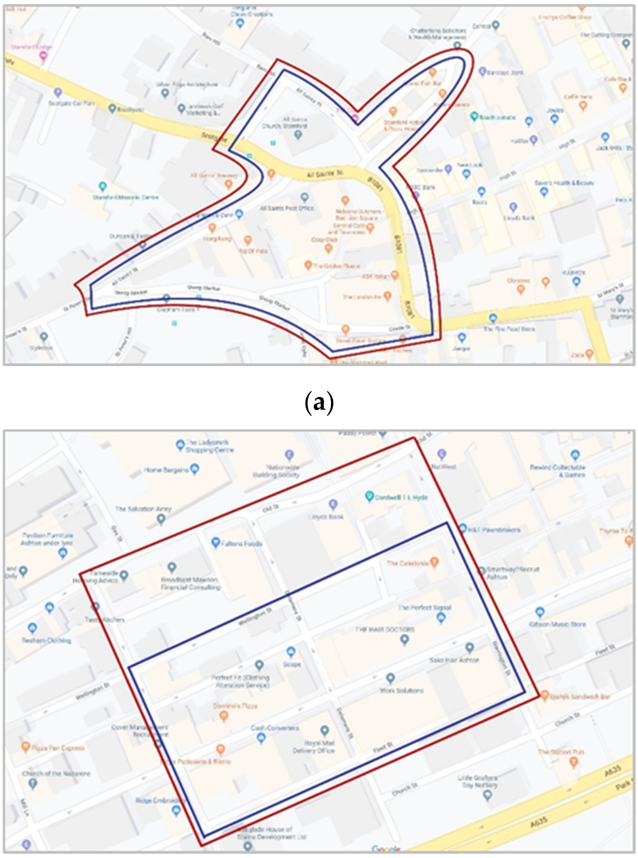
All of the participants had normal or corrected-normal eyesight, and none of the participants reported a history of mental illnesses. Seven records for the ORI task and three records for the SRS task were excluded because the sample rates (i.e., the percentage of eye movement data that is recorded) were below 70%. Therefore, 14 eye movement datasets (five from males) in the ORI task and 18 eye movement datasets (five from males) in the SRS task were analysed. Each participant received 160 RMB as compensation.

2.3. Apparatus

The experiment was conducted in a quiet lab in BNU. We used the Tobii T120 eye tracker (Tobii AB, Stockholm, Sweden; www.tobii.com) with the matching Tobii Studio 3.2.1 software in this study to record the participants' eye movements and export the data. The hardware included a Tobii eye tracker with a 60 Hz sampling rate and a 17-inch thin-film-transistor (TFT) monitor with a 1280 × 1024 pixel screen resolution. The recording accuracy of the eye tracker was 0.5° with 0.2° spatial resolution. The allowed head movement range was 0.2°. The tracking distance ranged from 50 to 80 cm, and in this experiment, the distance between the participant and the monitor was approximately 60 cm.

2.4. Materials

In this study, we used street views from Google Maps as the experimental material to eliminate the influence of other pedestrians [38], weather and traffic conditions. We chose part of Stamford, Lincolnshire, the United Kingdom and part of Ashton-under-Lyne, Greater Manchester, the United Kingdom as the irregular and regular road patterns, respectively (Figure 1, these maps were only for design purposes and were not shown to participants). To eliminate memory effects, we chose these two study areas in the UK to ensure that the participants were not previously familiar with the areas. The stimuli should be understandable to the participants, as they are university students and have taken the English exam in the National College Entrance Examination. None of the five participants who were recruited during the pre-test reported learning difficulties that were attributed to the English environment.



(**a**)

(**b**)

Figure 1. Experimental areas: (**a**) Stamford, Lincolnshire and (**b**) Ashton-under-Lyne, Greater Manchester. Red indicates the pre-test area and blue represents the experimental areas; participants were not provided with these maps.

Both of the study areas consisted mainly of business areas in small towns, where the majority of buildings had two or three floors and various signs and labels. Thus, the street view of the areas did not show an excessive number of people. The initial experimental areas were within the red framework, as shown in Figure 1. After the pre-test, part of the regular experiment area was cut off as the participants indicated that this area generated a larger workload and they needed more time to learn compared with the irregular area. The final experimental areas are shown in the blue framework.

On Day 1, when the participants were asked to remember the experiment areas, the controlling panels (e.g., the small map window and information box used on Google Maps) were hidden using the Google Maps application programming interface (API, Google [46]).

Street view screenshots (1024 × 640) of these areas were used as materials for the ORI and SRS tasks on Day 2. All the street view screenshots were unique and used only once. In these screenshots, names of streets were also hidden, as there are usually no names painted on streets. We did not use dynamic or interactive materials in the ORI and SRS tasks because the interaction itself might influence the visual attention distribution, and controlling the delay of updating was difficult if we used prepared dynamic videos.

2.5. Procedure

Day 1 As the participants did not know the study areas in any form before the experiment, they were asked to become familiar with these areas on Day 1. First, the researchers introduced the experimental timetable, including a sample task. The participants provided a signed consent form and were told that they could quit during any phase of the experiment.

The participants were then guided to "walk" along the boundaries of the irregular road pattern in Google Street View. They were allowed to navigate in the area freely by mouse or keyboard and were required to remember this area. Once the participants reported what they had remembered in this area, they were shown 10–12 screenshots of the street view and asked to indicate whether the screenshots displayed the roads that they had learned within the previous 5 s (for each screenshot). The participants needed to achieve at least 90% accuracy to begin the same procedure for the regular road pattern; otherwise, they needed to repeat learning and testing for the irregular road pattern.

Day 2 The participants were first shown and explained the instructions without using eye tracking. They needed to perform both ORI and SRS example tasks to ensure that they had fully understood the instructions (as described in [31], which employed the Baidu Streetview (Baidu Map: https://map.baidu.com/) near BNU to ensure the participants were familiar with the environment).

The ORI and SRS tasks with eye tracking then began. A five-point calibration was used. During this task phase, no further instruction was provided unless the task section changed (i.e., from ORI to SRS). The tasks were presented in the order of ORI tasks in an irregular road pattern (irORI), ORI tasks in a regular pattern (rORI), SRS tasks in an irregular road pattern (irSRS) and SRS tasks in a regular pattern (rSRS). Each part consisted of 10 subtasks. After the rORI part, the participants were allowed to rest their eyes. In each subtask, first, a white cross was presented in the middle of a black page for 1 s (as Figure 2 shows). Second, a screenshot of the destination (Figure 3a) was displayed for 6 s and, last, a screenshot of the current position was shown (Figure 3b for ORI and Figure 3c for SRS, tasks described with the figures). At this point, the participants were allowed to make a choice using their keyboard without time limitations. To prevent the participants from randomly guessing, they were allowed to press the space bar to skip a subtask if they could not recall the roads. Once they made their choice, the next subtask began with the black page with a white cross.

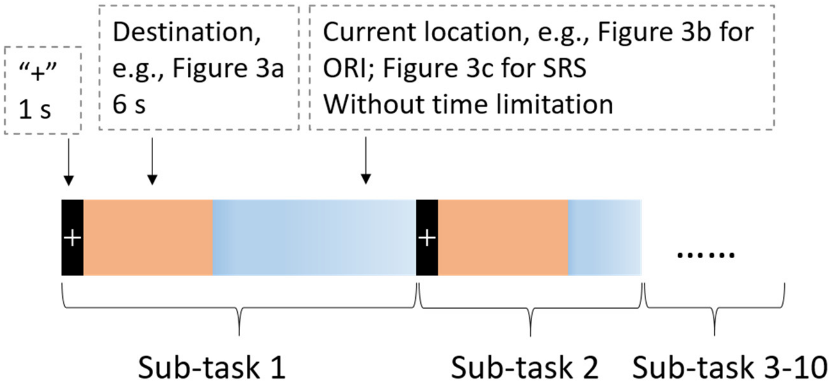


Figure 2. Sub-task design for each part.

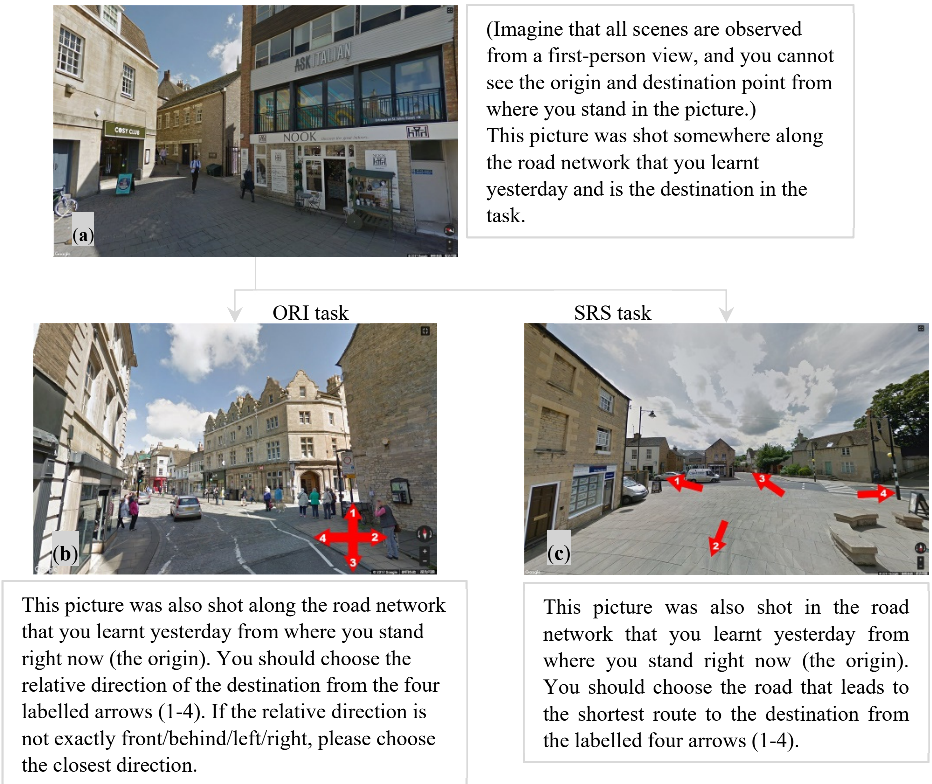


Figure 3. Example of experimental stimulus: (**a**): destination; (**b**): current position for orientation (ORI) task; (**c**): current position for shortest route selection (SRS) task. Tasks are described along the figures in grey text boxes.

2.6. Data Analysis

An I-VT (velocity-threshold identification) fixation filter with the default parameters in Tobii Studio was used for fixation filtering. We labelled the Road and Label areas of interest (AOIs) to conduct further analyses (Figure 4). The Road AOIs represented roads and walking areas on squares. The Label AOIs represented the signs of shops, front doors of buildings and recognizable advertisements. The areas covered by arrows were excluded because participants had to watch the arrows quite often. We used Quick Selection in Adobe Photoshop CS6 (Adobe Photoshop: https://www.photoshop.com/) to obtain the pixel number of each AOI and applied this value to represent the size of the AOI. If there were multiple Label or Road AOIs, the same kind of AOIs were aggregated into one AOI group.

Figure 4. Areas of interest (AOI) example: the yellow part is the Label AOI and the red part is the Road AOI.

Accuracy of Answers and response time were used to represent the participants' total performance. As information is processed during fixation, fixation-based metrics, especially duration, are usually used for task-related analysis [47,48]. For a more detailed review of eye movement metrics and their cognitive meaning, please refer to [32,49]. Four eye movement metrics were used (Table 1): time to first fixation, where a short time to first fixation means the object quickly attracts visual attention and has strong visual guidance [50,51]; average fixation duration, where a long average fixation duration indicates high processing difficulty [47,50,52,53] in pedestrian navigation; fixation count, where a high fixation count means a large processing load [54]; and fixation duration (also referred to as fixation time [47]), where a long fixation duration indicates that a long time is needed to process the information. As fixation count and fixation duration are strongly related to AOI size, we used the original value per 10,000 pixels in this analysis.

Table 1. Eye movement metrics.

Metric	Description	Unit
Accuracy of Answers	Number of subtasks that were skipped, misjudged or correctly completed by all participants.	count
Response Time	Time required by participants to make a decision (start with the origin point shown).	s
Time to First Fixation	Time spent before the AOI was first fixated on.	s
Fixation Duration	Total fixation duration within the AOI.	s/pixel number × 10,000
Fixation Count	Total fixation count within the AOI.	number/pixel number × 10,000
Average Fixation Duration	Fixation duration/Fixation count.	s

First, the outliers in the raw data were excluded based on the three-sigma rule. Second, we performed linear mixed model regression for the statistical test, as the data were based on a within-participant experiment and were not independent [55]. We predicted the eye movement metrics with road pattern and AOI category as fixed effects, and participants as random effect using Python's statsmodels module. We identified $p < 0.01$ as a significant influence and $p > 0.01$ as no significant influence.

Note that the statistical test was applied on data records based on AOIs instead of data records based on participants. Although seven samples for ORI tasks and three samples for SRS tasks were excluded, as mentioned in the Participants section, the test was performed on hundreds of data records.

3. Results

3.1. Overall Performance

Table 2 shows the accuracy of answers in different road patterns. In both the ORI task and the SRS task, participants performed better with irregular road patterns, as they skipped or misjudged fewer subtasks and made more correct choices.

Table 2. Task accuracy of answers (count).

Task	Road Pattern	Correct	Skipped	Incorrect
Orientation (ORI)	Irregular	56	28	56
	Regular	30	27	83
Shortest Route Selection (SRS)	Irregular	104	15	61
	Regular	92	19	69

The response time for all the four categories of tasks ranged from approximately 8 to 15 s. For the same kind of task, the response time does not show a considerable difference (Figure 5). The participants spent the same amount of time on the same tasks for different road patterns.

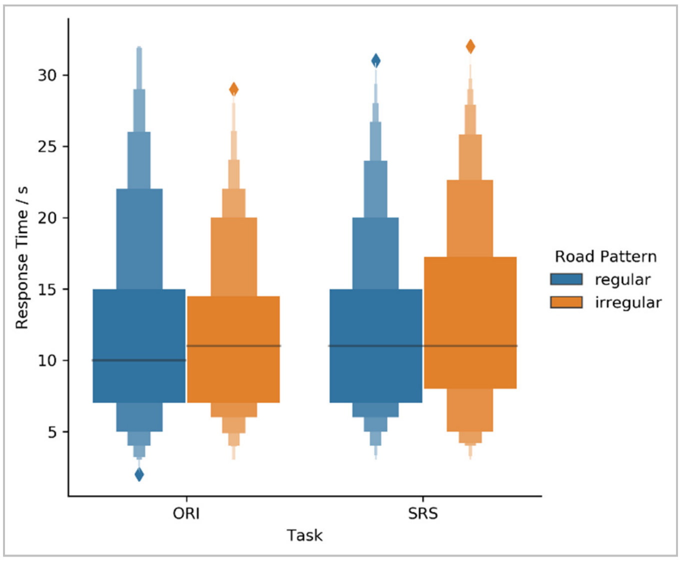


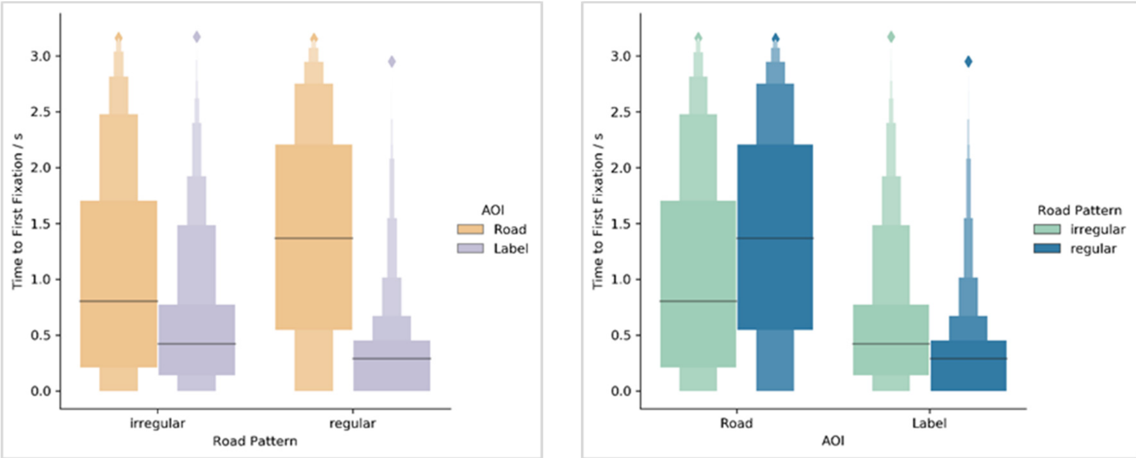
Figure 5. Statistics of response time.

3.2. ORI Task

3.2.1. Time to First Fixation

Figure 6 shows statistics of the time to first fixation in the ORI task. For both the irregular road pattern and the regular road pattern, the time to first fixation was shorter on Label AOIs than on Road AOIs (Figure 6a). Time to first fixation difference between irregular and regular road patterns in the

ORI task are shown in Figure 6b. For the Road AOI, time to first fixation was shorter with the irregular road pattern than with the regular pattern, whereas for the Label AOI, this time was longer.



(a) (b)

Figure 6. Statistics of the time to first fixation in the ORI task: (**a**): grouped by road pattern and (**b**): grouped by AOI category.

The results of linear mixed model regression of the time to first fixation in the ORI task are shown in Table 3. The coefficients of the road pattern and AOI category are −0.072 and −0.727, respectively. However, only the AOI category contributes significantly to the time to first fixation in the ORI task ($p < 0.01$). This result shows that participants first fixated on the labels and then fixated on the roads in both conditions. While participants tended to fixate on the roads faster or fixate on labels more slowly for irregular road patterns than regular road patterns, the difference is not significant.

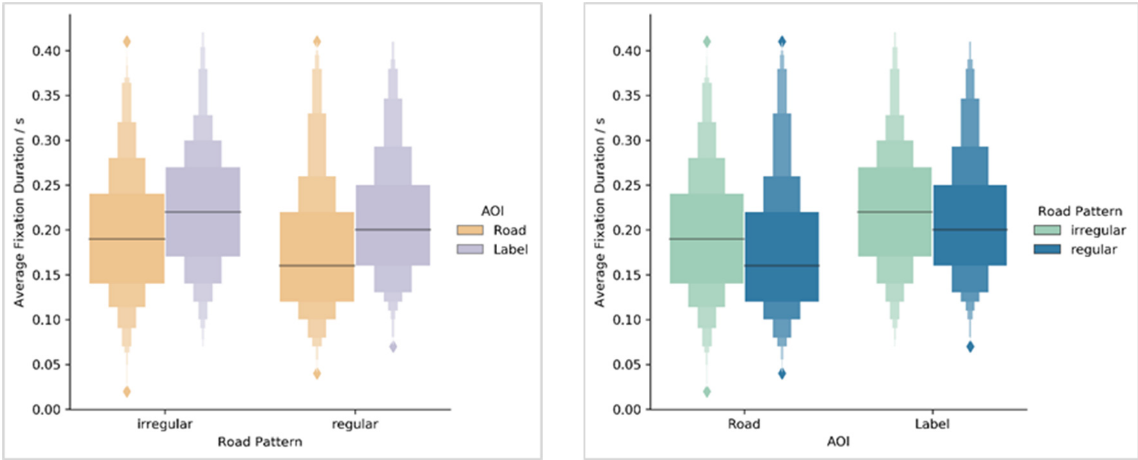
Table 3. Linear mixed model regression results of time to first fixation in the ORI task. Coeff, coefficient; SE, standard error; MSE, mean square error; Group Var, Group Variable.

	Coeff	SE	z	*p*-Value	MSE
Intercept	2.034	0.122	16.635	0.000	0.5536
Road Pattern	−0.072	0.055	−1.315	0.189	
AOI Category	−0.727	0.058	−12.522	0.000	
Group Var	0.001	0.006			

3.2.2. Average Fixation Duration

For both road patterns, the average fixation duration for the Label AOIs was longer than that for the Road AOIs, as shown in Figure 7a. For irregular road patterns, the average fixation duration for both roads and labels was longer than that for regular patterns (Figure 7b).

Table 4 shows the results of linear mixed model regression of the average fixation duration in the ORI task. The coefficients of the road pattern and AOI category are −0.013 and 0.024, respectively. Both the road pattern and AOI category contribute significantly to the average fixation duration in the ORI task ($p < 0.01$). The processing difficulty for the Label AOIs was higher than that for the Road AOIs. Participants made more efforts to process both road and label information with irregular patterns.



(a) (b)

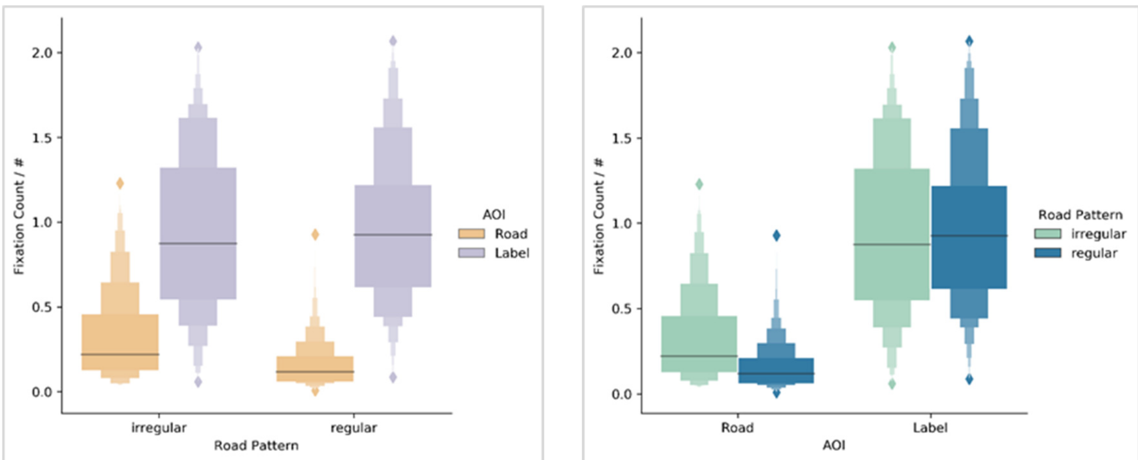
Figure 7. Statistics of average fixation duration in the ORI task: (**a**): grouped by road pattern and (**b**): grouped by AOI category.

Table 4. Linear mixed model regression results of average fixation duration in the ORI task.

	Coeff	SE	z	*p*-Value	MSE
Intercept	0.187	0.015	12.471	0.000	0.0037
Road Pattern	−0.013	0.004	−3.054	0.002	
AOI Category	0.024	0.004	5.795	0.000	
Group Var	0.002	0.014			

3.2.3. Fixation Count

As shown in Figure 8a, the fixation count for the Label AOIs was greater than that for the Road AOIs in both patterns. The fixation count for the Road AOIs was greater for irregular road patterns than that for regular patterns, and that for the Label AOIs was smaller than that for the irregular road patterns (Figure 8b).



(a) (b)

Figure 8. Statistics of fixation count in the ORI task: (**a**): grouped by road pattern and (**b**): grouped by AOI category.

Table 5 shows the linear mixed model regression results for the fixation count in the ORI task. The coefficients of the road pattern and the AOI category are −0.069 and 0.713, respectively. Both the road pattern and the AOI category contribute significantly to the fixation count in the ORI task ($p <$

0.01). Participants paid more attention to the Label AOIs with irregular road patterns than those with regular road patterns. Participants paid more attention to the Road AOIs with irregular road patterns and less to the Label AOIs with irregular road patterns.

Table 5. Linear mixed model regression results of fixation count in the ORI task.

	Coeff	SE	z	*p*-Value	MSE
Intercept	−0.371	0.057	−6.497	0.000	0.1256
Road Pattern	−0.069	0.026	−2.653	0.008	
AOI Category	0.713	0.026	27.556	0.000	
Group Var	0.007	0.011			

3.2.4. Fixation Duration

The fixation duration shows that the fixation duration for the Label AOIs was greater than that for the Road AOIs for both patterns (Figure 9a). The fixation count for the Road AOIs with irregular road patterns was greater than those with regular patterns, but the fixation durations for the Label AOIs with irregular and regular patterns were similar (Figure 9b).

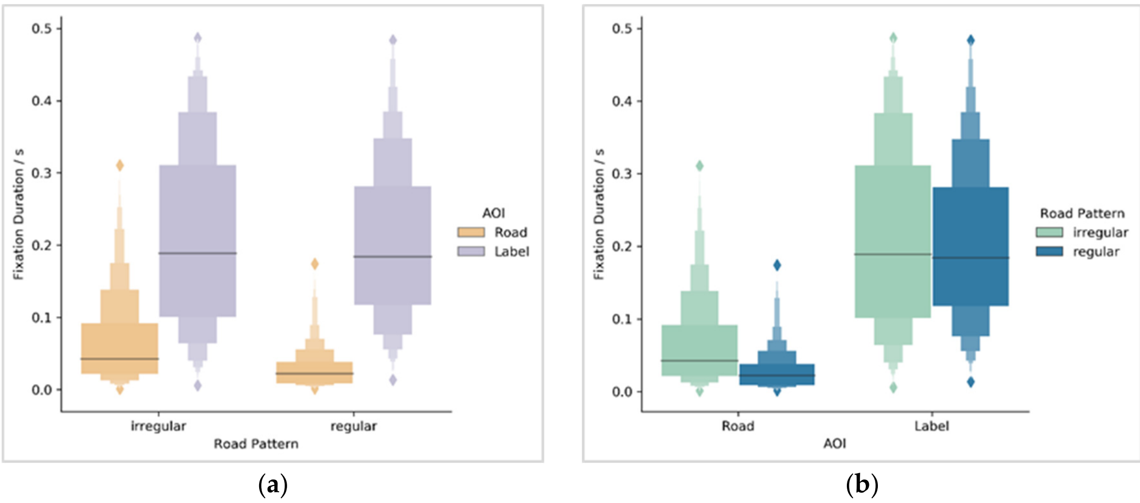


Figure 9. Statistics of fixation duration in the ORI task: (**a**): grouped by road pattern and (**b**): grouped by AOI category.

As shown in Table 6, the coefficients of the road pattern and the AOI category are −0.022 and 0.160, respectively. Both factors contribute significantly to the fixation duration ($p < 0.01$). Participants paid more attention to the Label AOIs. As the fixation durations for the Label AOIs are almost the same for irregular and regular patterns, we assume the influence of the AOI category results from the Road AOIs.

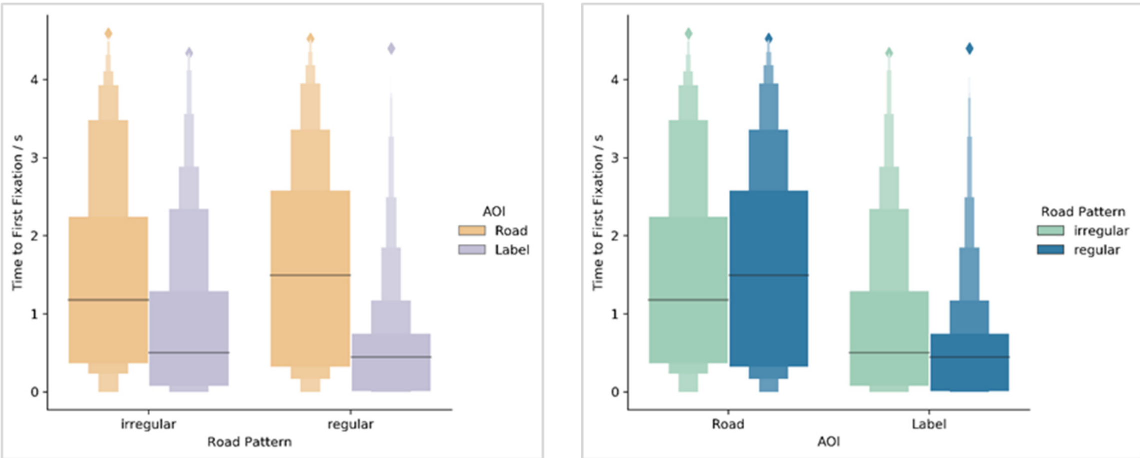
Table 6. Linear mixed model regression results of fixation duration in the ORI task.

	Coeff	SE	z	*p*-Value	MSE
Intercept	−0.078	0.016	−4.987	0.000	0.0073
Road Pattern	−0.022	0.006	−3.509	0.000	
AOI Category	0.160	0.006	25.693	0.000	
Group Var	0.001	0.006			

3.3. SRS Task

3.3.1. Time to First Fixation

The statistics of the time to first fixation in the SRS task are shown in Figure 10. As shown in Figure 10a, with irregular and regular road patterns, the time to first fixation for the Label AOIs was shorter than that for the Road AOIs. As shown in Figure 10b for the Road AOIs, the time to first fixation was shorter for irregular road patterns than for regular patterns. For the Label AOIs, the time to first fixation was slightly longer for irregular road patterns.



(a) (b)

Figure 10. Statistics of time to first fixation in the SRS task: (**a**): grouped by road pattern and (**b**): grouped by AOI category.

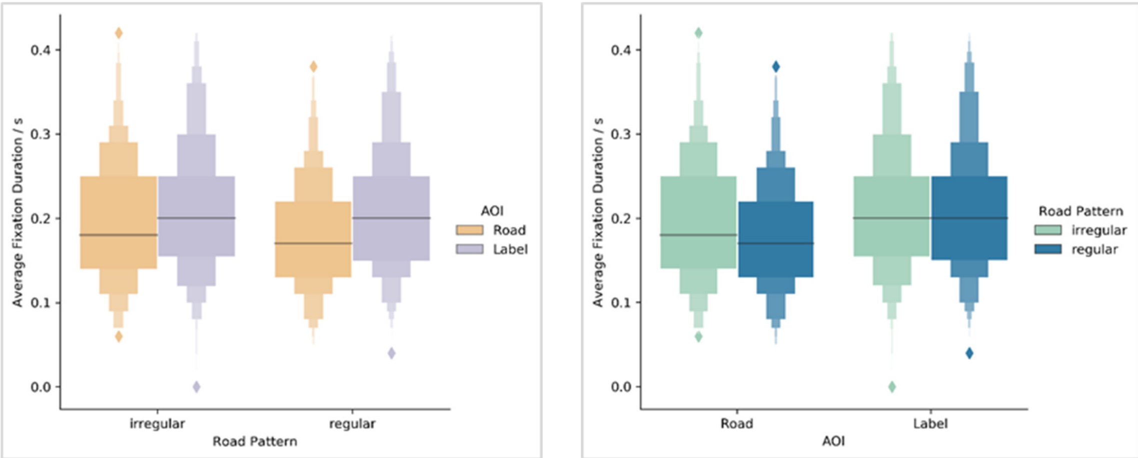
Table 7 shows the results of the linear mixed model regression for the time to first fixation in the SRS task. The coefficients of the road pattern and the AOI category are −0.100 and −0.812, respectively. However, the road pattern's contribution is not significant (p = 0.131). The time to first fixation in the SRS task is influenced only by the AOI category. The participants performed similarly as in the ORI tasks, in that they first fixated on the labels and then fixated on the roads.

Table 7. Linear mixed model regression results of time to first fixation in the SRS task.

	Coeff	SE	z	p-Value	MSE
Intercept	2.502	0.142	17.644	0.000	1.1803
Road Pattern	−0.100	0.066	−1.511	0.131	
AOI Category	−0.812	0.066	−12.23	0.000	
Group Var	0.016	0.011			

3.3.2. Average Fixation Duration

As shown in Figure 11a, the average fixation duration for the Label AOIs was longer than that for the Road AOIs for both irregular road patterns and regular patterns. As shown in Figure 11b, for the Road AOIs, the average fixation duration for the irregular road patterns was longer than that for the regular road patterns. For the Label AOIs, the average fixation durations for the roads and labels were similar.



(**a**) (**b**)

Figure 11. Statistics of average fixation duration in the SRS task: (**a**): grouped by road pattern and (**b**): grouped by AOI category.

Table 8 shows the results of the linear mixed model regression of the average fixation duration in the SRS task. The coefficients of the road pattern and AOI category are −0.009 and 0.021, respectively. Both factors contribute significantly ($p < 0.01$). The average fixation duration in the SRS task is influenced by both the road pattern and the AOI category. As in the ORI tasks, the processing difficulty was higher for the Label AOIs. Similar to different road patterns, the average fixation duration is the same for the Label AOIs. We assume that the influence of road pattern is derived from the Road AOIs. Processing Road AOI information with irregular road patterns is more difficult than that with regular road patterns.

Table 8. Linear mixed model regression results of average fixation duration in the SRS task.

	Coeff	SE	z	*p*-Value	MSE
Intercept	0.182	0.014	13.261	0.000	0.0034
Road Pattern	−0.009	0.003	−2.604	0.009	
AOI Category	0.021	0.003	6.170	0.000	
Group Var	0.002	0.015			

3.3.3. Fixation Count

Figure 12a shows that the fixation count for the Label AOIs was greater than that for the Road AOIs with both patterns. Figure 12b shows that the fixation count for both Road AOIs and Label AOIs with irregular road patterns was greater than that with regular road patterns.

Table 9 shows that the coefficients of the road pattern and the AOI category are −0.006 and 1.346, respectively. Only the AOI category contributes significantly ($p < 0.01$). The fixation count in the SRS task is influenced only by the AOI category. Similar to the ORI task, participants paid more attention to the Label AOIs with both road patterns.

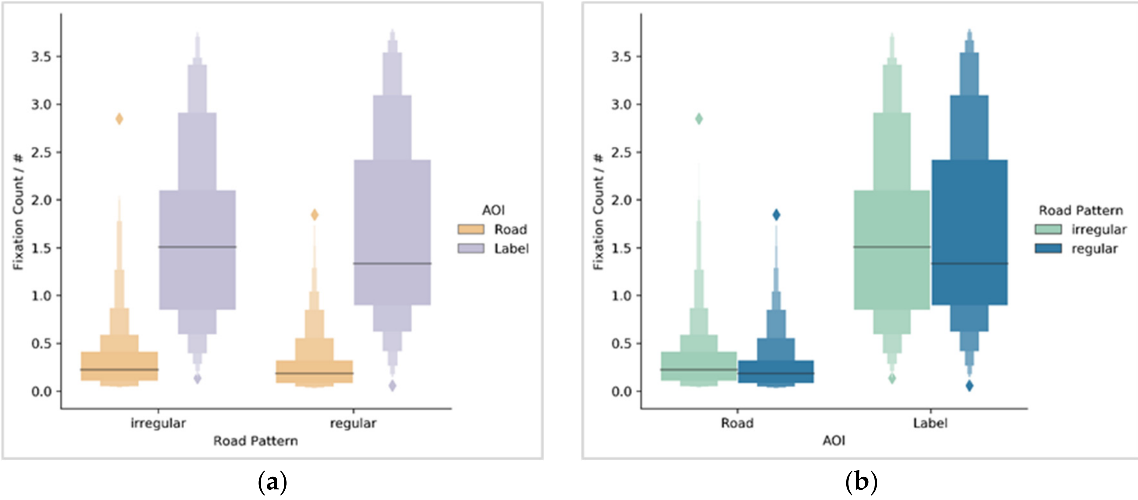


Figure 12. Statistics of fixation count in the ORI task: (**a**): grouped by road pattern and (**b**): grouped by AOI category.

Table 9. Linear mixed model regression results of fixation count in the SRS task.

	Coeff	SE	z	*p*-Value	MSE
Intercept	−1.030	0.091	−11.293	0.000	0.4805
Road Pattern	−0.006	0.043	−0.150	0.881	
AOI Category	1.346	0.043	31.363	0.000	
Group Var	0.009	0.009			

3.3.4. Fixation Duration

Figure 13a shows that the fixation duration for the Label AOIs was longer than that for the Road AOIs with both patterns. Figure 13b shows that the fixation duration for both Road AOIs and Label AOIs was longer for irregular road patterns than for regular patterns.

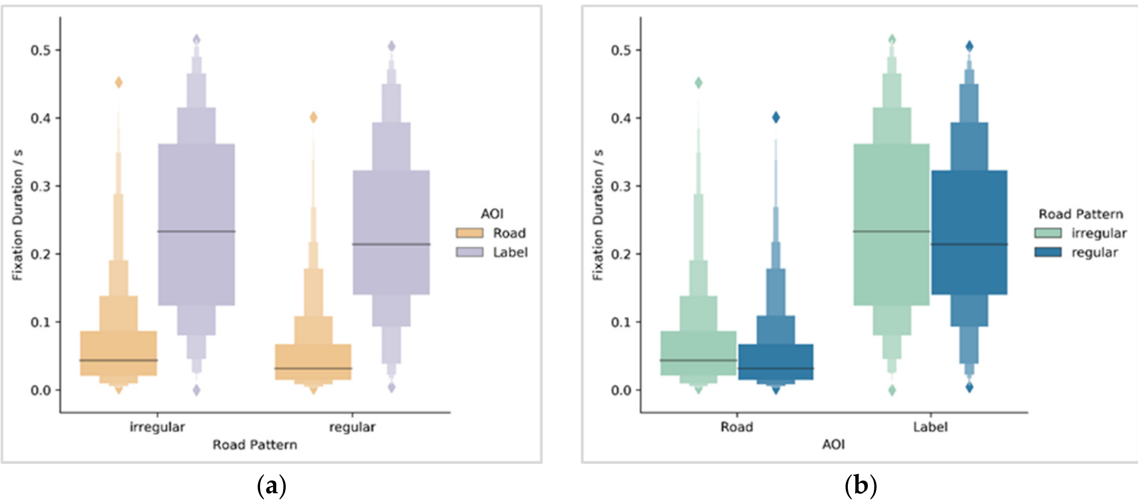


Figure 13. Statistics of fixation duration in the SRS task: (**a**): grouped by road pattern and (**b**): grouped by AOI category.

Table 10 shows that the coefficients of the road pattern and AOI category are −0.013 and 0.180, respectively. AOI category contributes significantly ($p < 0.01$) and road pattern's contribution is less significant ($p = 0.031$). The fixation count in the SRS task is influenced by the AOI category. Participants paid more attention to the Label AOIs with both road patterns. Although the participants tended to pay more attention for both the Road AOIs and the Label AOIs to perform tasks with irregular road patterns than tasks with regular road patterns, as in ORI tasks, the difference is not significant.

Table 10. Linear mixed model regression results of fixation duration in the SRS task.

	Coeff	SE	z	*p*-Value	MSE
Intercept	−0.099	0.014	−6.909	0.000	0.0087
Road Pattern	−0.013	0.006	−2.156	0.031	
AOI Category	0.180	0.006	28.627	0.000	
Group Var	0.001	0.004			

4. Discussion

4.1. Performance on Road and Label AOIs

This study shows that for both ORI and SRS tasks, participants first fixated on Label AOIs and then on Road AOIs with both irregular and regular road patterns, and they had more fixation counts and longer fixation durations per 10,000 pixels for Label AOIs than for Road AOIs. They also had longer average fixation durations for Label AOIs than for Road AOIs. Labels tended to grab participants' attention faster or receive more attention, and they also required more time to process.

This universal difference between Label and Road AOIs in this study is not surprising. The Road AOIs in this study only show road trends and intersections, and in regular road patterns, they are highly similar, whereas Label AOIs vary in shape, colour and texture and have semantic meaning. Therefore, the Label AOIs have a higher degree of recognition [56] and are more likely to be regarded as landmarks. This finding is consistent with that of Liao and Dong [57], who found that displaying 3D models, which are more salient than 2D maps, can improve map usability for male users. In general, rich label information should be provided for ORI and SRS tasks, and navigation systems should highlight the label information, for example, by using larger annotation or bright colours. On the other hand, with ORI tasks in irregular road patterns, participants also tried to rely on roads because the difference of average fixation duration was only marginally significant. This finding indicates that unique road patterns can also help wayfinding. Pedestrians may pay more attention to roads if the roads vary in texture or have some semantic meaning [56], for example, if traffic signs are painted on roads, especially on roads with unique patterns.

4.2. Performance in Different Road Patterns

Participants performed better with the irregular road pattern than the regular pattern for both tasks because they made more correct choices within the same amount of time. Since we chose areas with similar building styles, it could be concluded that the difference in the road pattern is the main cause of the performance difference. While Hirtle et al. [58] stated that oblique intersections can cause disorientation, this study shows that irregular road patterns with curvatures are better remembered. The unique intersections in irregular road patterns provide richer and more helpful information. The better performance for irregular road patterns may also explain pedestrians' preference for curvy roads in previous research [25].

The gaze data indicate that the road pattern's influence is caused by both roads and labels but is more related to roads. For both tasks, road pattern did not influence the time to first fixation for the Road AOI or Label AOI. For the ORI tasks, compared with the regular road pattern, participants had a longer average fixation for both Road AOIs and Label AOIs, a greater fixation count for the Road AOIs and a smaller fixation count for the Label AOIs with irregular patterns. The difference in the fixation duration was only observed in the Road AOIs; participants had a longer fixation duration for the Road AOIs with the irregular patterns. These differences indicate that ORI tasks with irregular road patterns are more demanding and are consistent with the findings of Liu et al. [31] based on fMRI. These authors found that when performing orientation tasks, the participants showed more activation in the functional brain areas that were related to decision-making (middle frontal gyrus and medial frontal gyrus) and eye movement (superior frontal gyrus) with an irregular road pattern than a regular pattern. In the SRS tasks, the difference in the average fixation duration between the road patterns was only shown for the Road AOIs, and participants had a longer average fixation duration for the Road AOIs with irregular road patterns. This difference indicates that for SRS tasks with irregular road patterns, roads were more likely to provide more information than they did for SRS tasks with regular road patterns. In both the ORI and SRS tasks, participants paid more attention to roads with irregular road patterns, where the roads had unique intersections or turns. Although colour, texture or semantic differences among the different roads were not observed, the roads provided important information based on the structure, which is consistent with the results obtained by Hirtle et al. [58], who found that unique intersections can be regarded as landmarks. Therefore, for navigation purposes, highlighting road patterns by indicating turns, intersections and curvatures could be helpful. This result encourages the construction of more unique intersections or irregular roads.

As Gibson indicated (summarized by Kitchin and Blades [59]), transitions (i.e., where the view changes considerably) are important for successful wayfinding. Transitions happen either when the pedestrian walks past a previous vista or when there is a turn. In regular road patterns, pedestrians always navigated forward and there were always sharp turns. However, in irregular road patterns, pedestrians might adjust the moving direction, which could be a hint about their location. In addition, with non-sharp turns, some of the buildings in previous views could remain visible after the transitions and help the pedestrian to orientate. The results show that people identify transitions mainly based on buildings, although the roads themselves are also important information sources regarding the transition for orientation. Thus, with irregular road patterns where the transitions are mostly unique, people tend to pay more attention to the roads than they do with regular road patterns.

4.3. Limitations

We identify some limitations that could be improved in future studies. The materials used in this study were street views from Google Maps, which were joint street views taken at different times. The inconsistencies of some shops may have caused confusion and further influenced the participants' performances. Although there were only a few inconsistencies in the study area, the results could be improved if the environment is properly controlled (e.g., in a virtual reality environment). People may also act differently in the 3D physical world compared with a highly controlled lab environment. For example, if there are people walking around, the participants may pay much more attention to the faces. People may also walk around the origin and gather information from different directions in the physical world. In addition, the experiment reported here was conducted in a fixed irregular–regular order, and an even better performance might be obtained for irregular roads if the order was counterbalanced because of learning effects. Testing how this difference changes as people become more familiar with the road network is an interesting future research direction.

5. Conclusions and Future Work

In this study, we aimed to identify whether gaze differences occurred between regular and irregular road patterns during orientation and route selection. We conducted an experiment in which 21 participants were asked to determine the relative orientation and choose the shortest route based on eye-tracking technology. We found that the performance was better for irregular road patterns than regular patterns. For both regular patterns and irregular patterns, labels provided the participants with more information, and the influence of the road pattern on the gaze was greater on roads than labels in both tasks. Participants tended to rely more on roads with irregular road patterns than those with regular patterns. The results contribute to further understanding the influence of road patterns on geospatial cognition and indicate that labels and unique road intersections or turns should be highlighted to support wayfinding and navigation tasks.

The results may have a limited ability to explain the influence of road patterns because the experiment was conducted on a desktop computer in a laboratory environment and based on newly learned road networks. Thus, the results may be improved by further investigation based on immersive or physical environments and on more familiar road networks.

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Data Availability Statement: The datasets generated and analysed during the current study are not publicly available as they contain information that could compromise privacy and consent of research participants, but they are available from the corresponding author on reasonable request.

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